THE

JOURNAL OF GEOLOGY

FEBRUARY–MARCH, 1912

AN EXPERIMENTAL CONTRIBUTION TO THE QUESTION OF THE DEPTH OF THE ZONE OF FLOW IN THE EARTH'S CRUST

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INTRODUCTION

In connection with an experimental study of the Flow of Rocks, on which the author has been for some time engaged and in which he has been assisted by grants from the Carnegie Institute of Washington, the question of the depth of the Zone of Flow beneath the surface of the earth has naturally presented itself. This subject has an interest and importance, not only as bearing upon many problems in geology, but also on one question at least of direct importance in mining, namely, that of the depth to which mineral-bearing fissures may extend in the earth's crust.

That the outer portion of the earth's crust was susceptible of subdivision into a Zone of Fracture and a Zone of Flow was set forth by Professor Heim in his great work *Untersuchungen über den Mechanismus der Gebirgsbildung*, and was based upon the data which he had obtained from his life-long studies in the Alps.[1] In this epoch-making work Heim states that as the result of his observations in the Alps he concludes that the upper surface of the Zone

[1] Albert Heim, *Untersuchungen über den Mechanismus der Gebirgsbildung*, Basel, 1878, Bd. II, 92.

of Flow for very resistant rocks, such as granites, is 2,200 to 2,600 meters or about a mile and a half below the surface of the earth, and considerably nearer the surface for limestone and other softer rocks. After thirty years of additional study Heim, in a recent paper, records his opinion that these depths are too small, that the Zone of Flow lies deeper within the earth's crust, but as to how much deeper he does not venture an opinion.[1]

President Van Hise in the interpretation of the results of his classic work on the ancient crystalline rocks of the United States in the district of the Great Lakes, reached a similar conclusion with reference to the twofold subdivision of the earth's crust, but placed the upper surface of the Zone of Flow at a considerably greater depth than Heim, namely, 12,000 meters or 7.4 miles.

Van Hise based his estimate on a mathematical calculation having as its starting-point the crushing weight of a cube of granite at the surface of the earth as determined by a testing machine in the ordinary manner adopted in testing the strength of building materials—granite being one of the strongest and at the same time one of the commonest rocks in the earth's crust. This calculation was made for Van Hise by Professor Hoskins who, taking the figures for the crushing strength of granite thus obtained, endeavored to calculate the depth below the earth's surface at which the pressure would be so great that all empty cavities would close as a result of plastic flow, even in the case of the hardest rocks like granite. This depth he fixed at four miles, or 6,520 meters. This is indicated by line "*a*" in Fig. 1. If however the cavities were filled with water Hoskins calculated that they would remain open to a depth of 6.4 miles, or 10,350 meters. This depth is shown by the line "*b*" in Fig. 1.

Van Hise then assumed an additional factor of safety, and took 12,000 meters as a depth at which not only all cavities would close but the hardest and most resistant rocks would flow—this being therefore the upper surface of the Zone of Flow in the earth's crust. This depth has been indicated by the line "*c*" in Fig. 1.

In order to make such a calculation, even in the very simple

[1] Albert Heim, *Geologische Nachlese*, No. 19 (*Vierteljahrschrift der Naturfor. Gesel. in Zürich*, 1908, 45).

case treated by Hoskins, certain assumptions must be made and the result obtained varies widely with these assumptions. Conse-

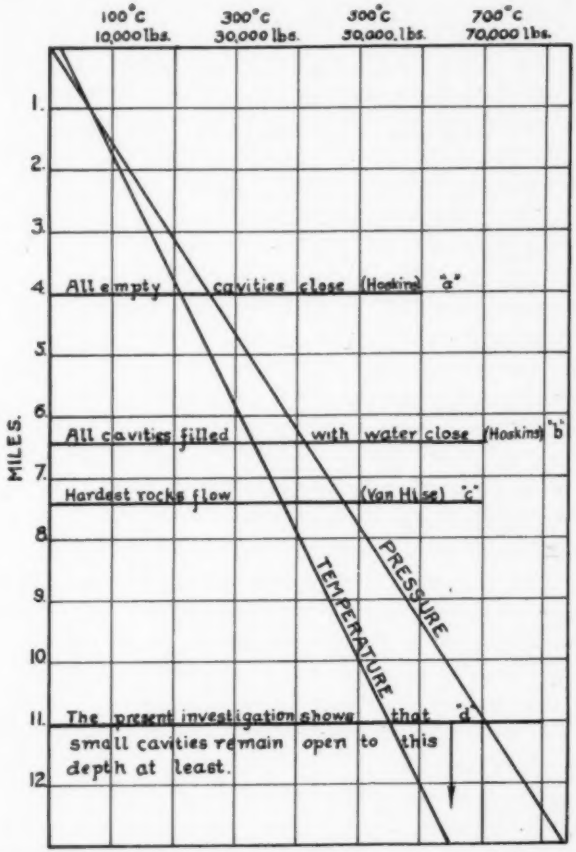


FIG. 1.—Showing the Pressures and Temperatures which are believed to exist within the Earth's Crust at successive depths to a distance of thirteen miles from the the surface. The temperatures are expressed in degrees Centigrade and the pressures in pounds per square inch. (see pp. 98 and 110).

quently, the figures obtained by Hoskins have not behind them the weight of a mathematical certainty. They are founded on

certain assumptions and have a probability no greater than the assumptions on which they are based.

The mathematical aspect of this question, however, as well as that of certain other questions arising out of the experimental results set forth in the present paper are treated at length by Mr. L. V. King, of the Department of Physics of McGill University, in the accompanying paper. As will be seen, Mr. King is of the opinion that the assumptions made by Mr. Hoskins are not permissible.

But even if the calculation were not based on these doubtful mathematical assumptions, a whole series of additional assumptions are made which very seriously affect the final result, as Van Hise himself points out. These are: (*a*) that rocks below the surface of the earth have the same strength as at the surface; (*b*) that the rocks constituting the earth's crust are all of the same kind; (*c*) that the temperature within the earth's crust is the same as that at the surface; (*d*) that the presence of water does not affect the character of the deformation; (*e*) that rocks yield as readily by fracture as by flow; (*f*) that rocks break as readily by fracture, when the deformation is slow as when it is rapid; (*g*) that the rocks whose crushing strength is taken as a datum are among the strongest in the earth's crust.

Van Hise believes that these assumptions are such that could we apply corrections for each of the factors concerned, we should find that these—with the exception of the first—"would tend to lower the figures given, that is to say, to bring the Zone of Flow nearer to the earth's surface." "But I suspect," he goes on to say, "that the various factors giving too great a depth are of far greater consequence than the one factor giving too small a depth."[1] He suspects the depth given by Hoskins is much too great, "probably twice too great."

The circumstance, however, that all these disturbing factors exist and that no account is taken of them in the calculation in question is frequently altogether forgotten and, consequently, positive statements are often made based upon this calculation, such as the following from a well-known book which has recently appeared.

[1] *A Treatise on Metamorphism*, 189.

We find that at a depth of about six miles beneath the surface the pressure must become so great that all rocks known to us would be crushed by it. If it were attempted, for example, to tunnel in rock at this depth, the roof of the tunnel would immediately collapse and the opening be entirely sealed up. The microscopic pores in the rock would likewise and for the same reason be closed.

As a matter of fact the figures for the depth of the Zone of Flow, which are under discussion, hang upon a slender thread of doubtful mathematical analysis enfolded by a cloak of many conjectures.

In his Presidential Address before Section G of the British Association for the Advancement of Science in 1904, Hon. Chas. A. Parsons discusses among other questions the possibility of sinking a shaft into the earth's crust to a depth of 12 miles, and in a letter which appeared in *Nature* (October 20, 1904) Geoffrey Martin expressed the opinion that at this depth the pressure would be so great that the walls of such a shaft, if it were constructed, would close in, owing to the viscous flow of the rock through which it passed. Parsons, in a note commenting on this letter, shows that a misplaced decimal point made the figures given by Professor Martin too high, and states that at the depth mentioned the pressure of the wall rock would amount to 44 tons per square inch, which in his opinion would be insufficient to close the shaft, adding:

I think that the evidence at present available leads to the conclusion that after a small amount of shrinkage of the shaft sides inward had taken place, a state of equilibrium would be established, enabling the surrounding rock in its state of great compression to withstand the so-called hydraulic pressure down to a depth from the surface of at least 12 miles.

He concludes,

It would however be interesting to subject a cylinder of granite or quartz rock carefully fitted into a steel mould and having a small hole bored through its center to a pressure of say 100 tons to the square inch and see what shrinkage in the hole would result.

As it seemed that important information might be obtained along the line suggested by Parsons, an experimental study of the question was undertaken, from which some rather interesting results have been obtained.

To go back for a moment to the important work of President Van Hise, it will be noted that in looking over the factors enumer-

ated by him as not having been taken into consideration, three are manifestly of much greater importance than the others in their bearing upon the depth of the Zone of Flow. These are: (1) the influence of pressure upon the rigidity of rocks in the deeper parts of the earth's crust; (2) the existence and influence of the higher temperature found at such depths; (3) the effect of long continued pressure as compared with pressure applied for short periods.

The other factors referred to are apparently of less importance. Thus the softer rocks—sandstone, limestone, etc.—occurring in the earth's crust do not extend to any considerable depth; the existence of water in the deeper parts of the earth's crust is a matter about which there is still a considerable amount of doubt; while it would seem that the strength of granite may be taken as fairly representative of that of the stronger rocks of the relatively superficial portion of the crust.

The question then arises as to whether it is possible, in approaching the question of the depth of the Zone of Flow from an experimental standpoint, to reproduce the conditions of rigidity, temperature and long continuance of pressure which exist in the earth's crust and thus give due value to these three hitherto doubtful factors in the problem. It would seem that this can be done approximately at least in the case of the first and second of these factors, but that it is practically impossible to accurately reproduce the third experimentally, for it is impossible in an experimental research to extend the duration of an experiment over decades or centuries. But even here some approach can be made to the reproduction experimentally of the conditions of this third factor, in the first place by extending the duration as much as possible, and secondly by the substitution of a relatively higher pressure during the shorter period within which the experiment is necessarily confined for the lower pressure existing in nature for longer periods, since a higher pressure during a shorter time will approximate at least in its results to the effects produced by a lower pressure for a longer time.

Before the attempt is made to reproduce the conditions of pressure and temperature which obtain within the earth's crust, it is necessary to form as clear a conception as possible as to what

these conditions really are. And here we are confronted with difficulties at the outset—for neither the pressure nor the heat existing as successive depths within the earth's crust can be calculated or otherwise determined accurately.

In order, however, to obtain some approximate measure of the pressure which exists at successive depths below the surface of the earth—and it is only the outermost portion of the crust extending to a depth of say 50 miles that comes into consideration for the present purpose—two assumptions, among others, will be made: (*a*) that the rocks composing the earth's crust are incompressible, and (*b*) that they are free from tangential stresses set up by the contraction of the earth's interior through secular cooling or by other causes. As a matter of fact, however, the rocks composing the crust are compressible and they are probably in most parts of the earth's crust in a state either of compressive or tensile stress. The first factor of compressibility, however, probably does not introduce any very serious error if omitted from consideration, but the second factor of tangential stress is more important and probably varies greatly not only at different points at or near the surface but at different depths below the surface. The data in our possession are inadequate to enable its influence to be calculated, but the investigations of Chamberlin, Woodward, Hoskins, and others[1] go to show that above the "Level of No Strain" great arches, if formed in the relatively cold surface crust, would be incompetent to sustain more than a small fraction of their weight and would thus collapse, tending to equalize the stresses in each successive zone.

For the purpose of this inquiry, the pressure at successive depths below the surface of the earth is assumed to be the weight of a column of rock equal in height to the depth in question. The specific gravity of the rock is taken as 2.8. These pressures are shown in Fig. 1.

It is also impossible to arrive at an accurate knowledge of the temperature within the earth's crust at successive depths below the surface. As is well known, the temperature gradient within the earth's crust shows considerable variations.

[1] See Chamberlin and Salisbury, *Geology*, I, 553 ff.

A careful study of these variations has recently been made by Königsberger and Mühlberg. According to these authors:

> It may be assumed that all over the earth in flat countries where the subsoil consists neither of comparatively recent eruptive rocks nor of deposits liable to change, there prevails a normal geothermic gradient. All deviations from the normal gradient are due to local influences: uneven surface of soil (mountains, valleys), the presence of great reservoirs of water (lakes, the sea), and heat producing processes in the interior of the earth or incompletely cooled eruptive masses.[1]

The average of the gradient of 32 borings in flat country in rocks which are neither of eruptive origin nor subject to considerable chemical alteration is given by Königsberger and Mühlberg as 1° Centigrade in 32.9 meters.

The geothermic gradient adopted as shown in Fig. 1 is based on this value.

The view that this temperature gradient continues uniformly downward in the earth's crust has been controverted by Strutt, who from investigations into the radio-activity of the rocks of the earth's crust concludes that the temperature rises uniformly to 1500°C., and then remains constant at that temperature to the center of the globe. This conclusion, however, does not affect the consideration of the present question, seeing that this temperature would not be attained until a depth had been reached which is much greater than those whose temperatures are made the subject of study in the present paper.

THE EXPERIMENTAL METHOD EMPLOYED

Two rocks were employed in this investigation and two series of experiments were carried out with each.

In the first series with each rock, the attempt was made to reproduce the conditions of pressure to which rocks are subjected at various depths within the earth's crust, both as to intensity and, as far as possible, as to duration; while in the second series of experiments the third element of temperature was also introduced.

[1] J. Königsberger and Mühlberg, "On Measurements of the Increase of Temperature in Bore Holes, etc." *Trans. Inst. of Mining Engineers*, London, 1910, XXXIX, Pt. IV, 9.

In every experiment a column of the rock, very accurately ground to the dimensions of .5 inch in diameter and 1.57 inch long, was taken and through it two holes were drilled. These holes were, as nearly as possible, .05 inch in diameter. One of these passed through the vertical axis of the column from top to bottom. The other passed transversely through the middle of the column, being at right angles to the other hole but a little to one side of it, so that the two holes did not actually intersect. A wire was then drawn to fit the hole exactly, so that the slightest change in the diameter of the hole could be detected by passing the wire into it.

A round bar of nickel steel, $3\frac{1}{4}$ inches long and $2\frac{1}{2}$ inches in diameter, was then taken and a hole very slightly smaller in diameter than the rock column was accurately drilled through it in the direction of the longitudinal axis. This bar was then heated slightly, and thus expanded just sufficiently to allow the column of rock to be slipped in so as to occupy a position in the middle of this bar or thick-walled tube. The tube was then allowed to cool. The perforated rock column enclosed in its steel tube is shown in Fig. 2. The rock was thus held firmly on all sides by the steel, but the size of the hole was such that the shrinking of the tube upon the column did not compress the rock more than was required to effect a perfect mechanical fit, and in this way to give the requisite lateral support to the rock when the latter was submitted to compression in a vertical direction. Preliminary experiments showed that this operation did not in the slightest degree affect the size of the holes which had been bored through the column, and also showed that if the latter were unsupported below, a load of 7,250 lbs. on its upper end would shove it down through the tube.

If the experiment was to be conducted at ordinary temperatures, a disk of paper was then placed on either end of the column to equalize the pressure and two pistons of hardened "Novo" steel, ground so as to pass easily into the ends of the tube were inserted, by means of which pressure could be brought to bear upon the enclosed column. The whole was then placed in a powerful press and the enclosed rock submitted to a pressure equivalent to any required depth beneath the surface of the earth for a period

varying from a few hours to two and a half months. Upon the conclusion of the experiment, the apparatus was removed from the press; the pistons, which could be readily withdrawn, as well as the disks of paper if any had been employed, were removed. The question as to whether the vertical or longitudinal hole had under-

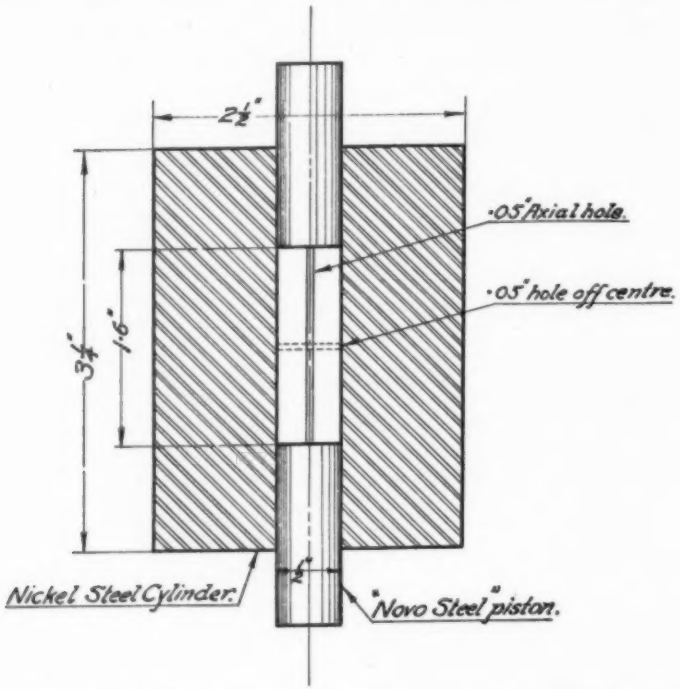


FIG. 2.—Showing the Column of Rock with a vertical and a transverse hole drilled through it, enclosed in a heavy tube of nickel steel.

gone any constriction was determined by ascertaining whether the wire would still pass through the hole which it had been drawn to fit, the slightest change in size being readily detected. The steel tube with its enclosed rock column was then placed in a lathe and the steel surrounding the middle portion of the column was turned off until only a film remained. This, where it covered the

ends of the transverse hole, was then removed, and the question as to whether there had been a constriction of the transverse hole was determined by attempting to pass the wire through it.

In those experiments in which the element of heat was introduced, the tube with the enclosed column was placed before compression in a suitably constructed apparatus in which it could be maintained at a constant temperature, during the experiment, the temperature being measured by a properly calibrated thermo-electric couple.

For the purpose of experimental investigation, it was important to select rocks which not only represent the chief types composing the earth's crust but which also possess physical characteristics which render them suitable for experimental purposes, that is to say, rocks which are massive, rather fine in grain, uniform in character, and free from cracks and other flaws.

Two rocks which fulfil these conditions excellently are:—(1) the Lithographic Limestone from Solenhofen, Bavaria; (2) the Red Granite from Westerly, Rhode Island.

LITHOGRAPHIC LIMESTONE, SOLENHOFEN, BAVARIA

This may be taken as representing the softer sedimentary type of rocks which are found more abundantly at or near the surface in the upper portions of the earth's crust. The Solenhofen limestone is very fine in grain, very massive in character, and of a buff color. It breaks with a splintery or choncoidal fracture, and Heim speaks of it as one of the most brittle of rocks. A chemical analysis showed that the variety employed in these experiments consisted of carbonate of lime holding 3.52 per cent of impurities. It has a specific gravity of 2.603 when dry and is slightly porous, as shown by the fact that when allowed to remain under water in vacuo for 24 hours it absorbs 1.63 per cent of water.

In order to ascertain the crushing strength of the rock as determined in the manner usually employed in the case of building stones, etc., a series of six 2-inch cubes were very carefully sawn out of a block of the limestone, and having been accurately ground, were tested in compression, observing all the precautions required to attain the most accurate results. These determinations were

carried out in the Testing Laboratories at McGill University, a 100-ton Wicksteed machine being employed, and gave the following results:

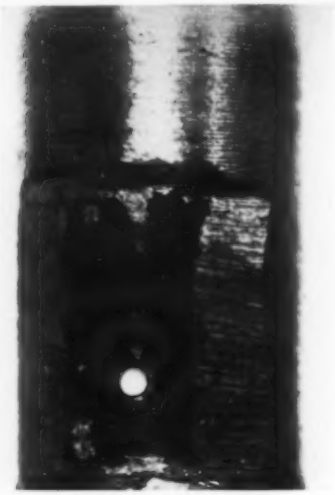
40,600	lbs.	per	square	inch
28,400	"	"	"	"
29,635	"	"	"	"
33,788	"	"	"	"
32,725	"	"	"	"
32,750	"	"	"	"
Average = 32,980				

The average crushing strength of the Solenhofen limestone is, therefore, 32,980 lbs. per square inch. It is thus seen to be an extremely strong rock; stronger, in fact, than an ordinary granite under compression.

Four experiments were first made with columns of Solenhofen limestone, the pressure being increased in each successive experiment so as to represent successively greater and greater depths within the earth's crust, the element of time being also varied. These experiments were all, however, conducted at the ordinary temperature. The results are shown in Table I on p. 109.

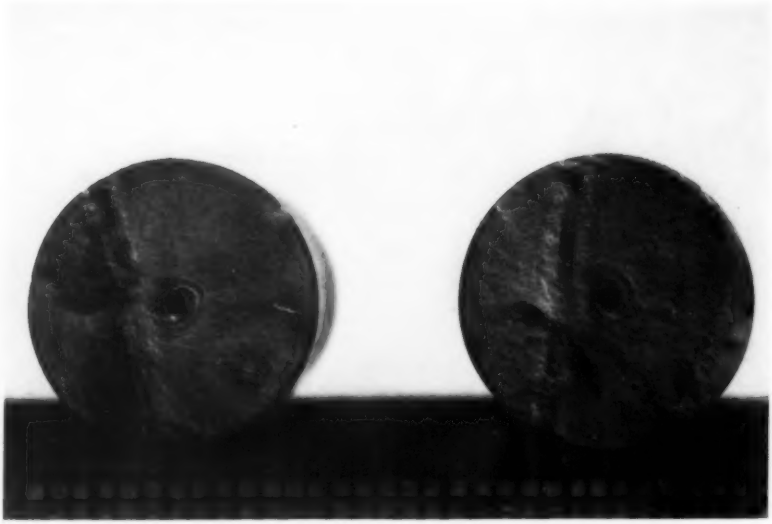
It will be seen from these experiments, that at the ordinary temperature no trace of movement could be detected in the rock at a pressure equivalent to a depth of 15 miles below the earth's surface, even after the pressure had been continuously applied for two and a half months. When, however, the pressure was increased to that which is supposed to exist within the earth's crust at a depth of 20 miles below the surface, the experiment being continued for two and a half months, a certain movement was observed. At a pressure representing a depth of 30 miles and to a still more marked extent at a pressure equivalent to a depth of 40 miles, movements had taken place in 7 hours which resulted in the partial filling of the holes passing through the column. As will be noted, a depth of 31 miles represents a pressure of 100 tons to the square inch.

It is thus seen that Solenhofen limestone at the ordinary temperature and under conditions of cubic compression—which are the conditions of pressure to which it is subjected in the earth's



a

b



c

crust—will retain its form and will not flow into holes traversing it even when submitted for months to a pressure three times as great as would suffice to crush it instantly under the ordinary conditions obtaining at the surface of the earth.

TABLE I

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF SOLENHOFEN LIMESTONE—AT THE ORDINARY TEMPERATURE—ARE SUBMITTED TO PRESSURES EXISTING AT SUCCESSIVE DEPTHS WITHIN THE EARTH'S CRUST

No. of Experiment	Pressure Pounds per Square Inch	Kilos. per Sq. Cent.	Depth below Surface of the Earth Represented by the Pressure	Duration of the Pressure	Results
359.....	96,000	6,750	15 miles	2½ mos.	No movement of any kind. (See Plate I, Fig. *a*)
360.....	128,000	9,000	20 miles	2½ mos.	Transverse hole smaller. Vertical hole partly filled. (See Plate I, Fig. *d*)
382.....	193,000	13,570	30 miles	7 hrs.	Transverse hole unaltered. Vertical hole partly filled.
520.....	200,000	14,060	31 miles	½ hr.	Transverse hole flattened. Vertical hole mostly filled. (See Plate I, Fig. *b*)
383.....	257,000	18,070	40 miles	7 hrs.	Transverse hole flattened. Vertical hole mostly filled. (See Plate I, Fig. *c*)

The movement noted in the cases of experiments 520 and 383—representing depths of 31 and 40 miles—seems to be of the nature of flow, so far as it affects the transverse holes, these holes becoming flattened. But as shown in the descriptions of Plates I and II, the movement takes place by the development of minute fractures along the course of the vertical holes, small fragments of the rock becoming detached from the walls. The author desires to express his thanks to Dr. J. A. Bancroft of McGill University, to whom he is indebted for the photographs from which these prints were taken.

A second series of experiments was then made with a view to ascertaining the effect produced by the introduction of the factor of heat.

According to the investigations of Debray,[1] the highest temperature to which calcite can be submitted in open vessels without decomposition is 450°C. This is the temperature which is supposed to exist at a depth of nine miles below the surface of the earth.

Perforated columns of the limestone, identical in size and shape with those employed in the first series of experiments, were enclosed in heavy tubes of steel as before. The tubes having been heated to a temperature somewhat higher than 450°C., the column was inserted and the tube then allowed to cool and contract about it. The steel pistons were inserted in the usual manner and the whole being placed in a specially constructed heating apparatus, the rock was maintained at a temperature of 450°C. while submitted to the required pressure.

An investigation into the relative expansion of the nickel steel and the Westerly granite carried out by N. E. Wheeler, B. Sc. of the Department of Physics of McGill University, shows that with a gradually rising temperature the granite at first expands more slowly than the steel and then more rapidly.[2] The expansion curves intersect, i.e., both materials expand equally at a temperture of 400°C., and with the temperature of 450°C., at which all the experiments with two exceptions were conducted, the difference in expansion of the two materials is extremely small, the expansion of the granite being slightly greater, which serves only to cause the enclosing tube to hold the granite column a little more firmly.

As it was impossible with the apparatus employed to maintain an absolutely constant temperature without the continuous attention of the experimenter, these experiments at high temperatures could not be extended over periods of several months as in the case of the experiments conducted at ordinary temperatures. The shorter time during which the experiment lasted, however, was in a manner compensated for by increasing the pressure, a higher

[1] C.R., 1867, 603.

[2] "On the Thermal Expansion of Rock at High Temperatures," *Trans. Roy. Soc. of Canada*, 1910.

pressure for a relatively shorter time producing in the case of plastic deformation the same effect as a relatively lower pressure for a longer period. While therefore the temperature, except in the last experiment, was maintained at 450°C., equivalent to a depth of 9 miles below the surface, the pressure was increased until it was equivalent to a depth of 15 miles below the surface, while the time varied from 70 seconds to 70 hours. The results obtained are set forth in the following table.

TABLE II

TABLE SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF SOLENHOFEN LIMESTONE—HEATED TO 450°C.—ARE SUBMITTED TO PRESSURES EXISTING AT DEPTHS OF 10 AND 15 MILES WITHIN THE EARTH'S CRUST

No. of Experiment	Heat	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Equivalent to Pressure Employed	Time	Results
480.....	450°C.	64,000	4,500	10 miles	7 hrs.	Holes remain unchanged. No movement of any kind.
374.....	450°C.	96,000	6,750	15 miles	70 secs.	Holes become slightly contracted.
362.....	450°C.	96,000	6,750	15 miles	7 hrs.	Holes become slightly contracted.
367.....	450°C.	96,000	6,750	15 miles	25 hrs.	Holes become slightly contracted.
370.....	450°C.	96,000	6,750	15 miles	70 hrs.	Holes become slightly contracted.
371.....	450°C.	96,000	6,750	15 miles	70 hrs.	Holes become slightly contracted.
365.....	490°C. to 513°C.	96,000	6,750	15 miles	70 hrs.	Transverse hole closed completely.

In this series of experiments it is to be noted that when the rock is submitted to the maximum temperature which can be employed without decomposing it, namely 450°C., which is equivalent to a depth of nine miles below the surface of the earth, no effect is produced if the pressure be raised to that which obtains at a depth of 10 miles. If, however, the pressure is still further increased till it reaches that to which the rock would be exposed

at a depth of 15 miles, a slight diminution in the diameter of the holes is observed, even if this pressure is only maintained for a period of 70 seconds. This movement, however, is not increased even if the rock be maintained at this pressure and temperature for an additional period of 70 hours. In the last experiment, however, when the heat rose for a time to 513°C. the transverse hole, as noted, became completely closed, which may have been connected with a partial disassociation of the Ca CO_3 molecule caused by the high temperature.

GRANITE, WESTERLY, RHODE ISLAND, U.S.A.

A knowledge of the behavior of this rock under deep seated conditions is of especial importance, because it is a typical representative of the great class of plutonic igneous rocks which make up so large a portion of the earth's crust.

This well-known rock is a fresh, fine-grained, massive, pale pink granite, composed essentially of biotite, microcline, orthoclase, and quartz. A detailed description of its microscopic characters as well as the results of a study of its elastic constants are given in Publication No. 46 of the Carnegie Institute of Washington.[1]

The crushing strength of the granite was determined on 2-inch sawed cubes, all the precautions referred to in the case of the Solenhofen limestone being employed to secure accuracy. The results were as follows:

1st cube	= 28,340	lbs. per square inch
2d cube	= 26,410	" " " "
Average	= 27,375	" " " "

It will thus be observed that the rock is not quite so strong as the Solenhofen limestone under the ordinary conditions of a test for crushing strength.

Columns of the granite were prepared, bored, and placed in their enclosing tubes of steel in the manner already described. As in the case of the Solenhofen limestone, a series of experiments

[1] Adams and Coker, *An Investigation into the Elastic Constants of Rocks*, etc., Carnegie Institute of Washington, Washington, 1906.

were first made at the ordinary temperatures. The following table shows the results obtained:

TABLE III

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF WESTERLY GRANITE—AT THE ORDINARY TEMPERATURE—ARE SUBMITTED TO PRESSURES EXISTING AT SUCCESSIVE DEPTHS WITHIN THE EARTH'S CRUST

No. of Experiment	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Represented by the Pressure	Duration of Pressure	Results
361.....	128,000	9,000	20 miles	2½ mos.	Holes unaltered—No movement.
373.....	160,000	11,250	25 miles	2½ mos.	Holes unaltered—(See Plate II, Fig. a).
356.....	199,000	13,990	30.86 miles	15 hrs.	Holes unaltered—No movement—
357.....	200,000 (100 tons to sq. inch)	14,060	31 miles	2½ mos.	Transverse hole unaltered. Vertical hole partly closed at one end by rock powder.
358.....	222,500	15,640	35 miles	2½ mos.	Transverse hole completely filled. Vertical hole largely filled with rock powder—(See Plate II, Fig. b).

It is thus seen that granite at the ordinary temperature, but under the conditions of cubic compression which obtain in the earth, will sustain a load of about 100 tons to the square inch, that is to say, a load rather more than seven times as great as the crushing load of the granite at the surface of the earth under the conditions of the ordinary laboratory test.

In this connection an observation made by P. W. Bridgman is of interest, namely, that under an external hydrostatic pressure amounting to 24,000 atmospheres, or 360,000 pounds to the square inch, continued for 3 hours the cavity of a sealed glass tube did not close or show any sensible change in size or form.[1]

Reference has been made to the nature of the movement observed in the case of the Solenhofen limestone, which seemed to be due in part to flow and in part to fracture.

[1] Quoted by R. A. Daly in his paper on the "Nature of Volcanic Action," *Pro. Am. Acad. of Arts and Sciences*, June, 1911, p. 53.

In the case of the granite the holes when filled are closed by what appear to be minute fragments of granite detached from the walls. In the case of experiment 358, after the removal of the steel the vertical hole as seen from either end was still open and was unaltered in size or shape for a distance of .08 and .24 inch respectively. Beyond that, however, it was blocked up. On removing the steel so as to expose the extremities of the transverse hole, it was found that one end of this hole was completely filled up, no trace of the opening remaining. The locus of the hole was occupied by what seemed to be a part of the rock, finer in grain than the rest and which looks as if it were a perfectly compacted mass of powdered granite. The other extremity of the hole had also been completely closed, although an outline marking its original position could be seen—it was filled with finely granular material clearly crushed granite, imbedded in which were a few relatively larger fragments giving to the whole the appearance of a breccia.

In order to eliminate any error which might be conceived to have been introduced by the pistons expanding under the load and pressing against the sides of the steel tube, thus reducing the amount of pressure exerted on the rock and also to give the rock a better chance to deform by the application of the pressure to the center of the end faces instead of over the entire surface of the faces in question, another experiment was arranged in which the column and its enclosing tube were identical in all respects with those already described but the pistons were .4 inch in diameter while the column had the usual diameter of .5 inch. The proper load to give a pressure of 160,000 lbs. per square inch, equivalent to a depth of 25 miles below the surface, was then applied by this smaller piston to the center of the end faces of the column, for a period of two and a half months, but no change whatever was produced in either the transverse or the vertical hole.

A second series of experiments was then carried out with the Westerly granite in which the factor of heat was introduced.

For the same reason as mentioned in the case of the Solenhofen limestone, the duration of the experiment was necessarily shorter than in the case of the experiments conducted at the ordinary temperature. The results of the experiments are as follows:

TABLE IV

SHOWING THE EFFECTS PRODUCED WHEN COLUMNS OF WESTERLY GRANITE—HEATED TO 450°C. AND 550°C.—ARE SUBMITTED TO THE PRESSURE EXISTING AT A DEPTH OF 15 MILES WITHIN THE EARTH'S CRUST

No. of Experiment	Heat	Pressure Lbs. per Sq. Inch	Kilos. per Sq. Cent.	Depth Equivalent to Pressure Employed	Time	Results
375.....	450°C.	96,000	6,750	15 miles	70 secs.	Holes unaltered. No movement.
376.....	450°C.	96,000	6,750	15 miles	70 hrs.	Holes unaltered. No movement.
381.....	550°C.	96,000	6,750	15 miles	70 hrs.	Holes unaltered. No movement.

As before mentioned, the temperature of 450°C. is that which exists at a depth of 9 miles below the surface, while a temperature of 550°C. is that which is found 11 miles below the surface.

Experiment 381 is one the results of which are of especial interest, for it shows that under the conditions of temperature which exist at a depth of 11 miles below the surface of the earth, open cavities in granite—at least those of relatively small dimensions—*will not close even if the factor of time is allowed for by increasing the pressure over and above that which occurs at a depth of 11 miles by nearly 50 per cent.*

It is further to be noted that this depth of eleven miles (see Fig. 1) is not the extreme depth at which experiment shows that open cavities may exist. They may be present at still greater depths, but the fact that the steel by which the lateral resistance was secured experimentally commences to soften at temperatures of a little over 550°C. makes it impossible to push the experimental investigation by the method employed, to the study of the deportment of the rock at higher temperatures, that is to say, at greater depths.

THE DEPTH TO WHICH MINERAL VEINS AND ALLIED DEPOSITS MAY EXTEND

The present investigation seems to have a rather important bearing on a question of great economic importance, namely, the depth to which mineral veins and replacement deposits may extend in the earth's crust. It must first be noted that the question of

the size of a cavity is one which must be considered in this connection. In the accompanying paper Mr. King has investigated this subject mathematically and shows that in the case of any given rock a pressure might be reached which would be sufficient to crush in larger cavities, but the collapse of the walls instead of leading to the complete closing of the cavity in question would merely result in the formation of a number of smaller spaces, which would remain open permanently or which could only be closed by a greatly increased pressure.

This factor has been eliminated in the present investigation by having the holes in the case of all the experiments identical in size and relatively small.

It is the depth to which these smaller cavities and passages will remain open that is the really important one in connection with the question of the depth to which mineral deposits may extend. For although a great fissure vein may have been developed by the filling of a great fissure, it is considered by some authorities that the crystallographic force of the growing minerals filling the vein has had an important influence in opening up a comparatively narrow fissure, thus making a relatively wide vein in what was originally a comparatively narrow crack. But whether this be so or not, a class of deposits which are much more numerous and more important than "true fissure veins," namely replacements, do not require any originally wide fissures for their development, but are formed by the passage of mineralizing solutions or vapors through narrow cracks or fissures, which serve merely to give such solutions or vapors under high pressures a passage into and through the rock, which they attack and alter and in which they deposit their burden of ores and other valuable minerals by a process of replacement. All, therefore, that is needed for the formation of such deposits are very narrow cavities or fissures to give the mineral bearing solutions access to the rock in which the ores are to be concentrated. Many deposits in shear zones and shattered strips of rock are of this character, as well as other replacement deposits in which the lines of the original fissures are now entirely obliterated.

Whatever, therefore, may be the fate of great yawning chasms if these are formed within the earth's crust at the depths under

consideration in this paper, it is clear that if these are crushed in, smaller cavities will survive even in the crushed mass of rock formed by the collapse of the walls of such a cavity, and will afford ample passage for solutions, vapors, etc., and, therefore, provide the conditions required for the deposition of mineral deposits of the replacement type at least at the great depths in question.

SUMMARY OF CONCLUSIONS

1. The calculations which have been made as to the depth below the earth's surface at which all cavities in the earth's crust would be closed by plastic flow, based on the crushing strength of rocks at the surface of the earth, are erroneous.

2. At ordinary temperatures but under the conditions of hydrostatic pressure or cubic compression which exist within the earth's crust, granite will sustain a load of nearly 100 tons to the square inch, that is to say, a load rather more than seven times as great as that which will crush it at the surface of the earth under the conditions of the usual laboratory test.

3. Under the conditions of pressure and temperature which are believed to obtain within the earth's crust, empty cavities may exist in granite to a depth of at least 11 miles. These may extend to still greater depths, and if filled with water, gas or vapor, will certainly do so, owing to the pressure exerted by such fluids or gases upon the inner surfaces of such cavities or fissures.

4. Since the existence of open spaces through which aqueous solutions, vapors, or gases can traverse a rock is a factor in the development of mineral veins and replacement deposits, such veins and deposits may be formed within the earth's crust to a depth of at least 11 miles below the surface. That is to say, they may extend to a much greater depth than it is possible to follow them by any method of mining now employed.

DESCRIPTION OF PLATES

PLATE I

FIG. *a*.—Shows a column of Solenhofen limestone (Exp. 359) which has been submitted to a pressure equivalent to a depth of 15 miles within the earth's crust for 2½ months. The steel tube has been partially removed so as

to expose the transverse hole. This latter is seen to have been unaffected by the pressure.

FIG. *b*.—This is a column of Solenhofen limestone (Exp. 520) which has been submitted to a pressure of 100 tons to the square inch equivalent to a depth of 31 miles below the surface of the earth, for half an hour. The steel which enclosed it has been completely removed. There has been a slight movement of the nature of plastic flow developed in the rock, owing to which the transverse hole originally circular in outline has been flattened so that it now presents a lenticular cross-section.

FIG. *c*.—This is experiment 383. The column of Solenhofen limestone was submitted to a pressure equivalent to a depth of 40 miles below the earth's surface—for seven hours. The steel tube was then removed but in the process the column broke in two along the line of the transverse hole (seen at the top of the photograph) and also split vertically along the line of the vertical hole. A vertical section of one-half of the column is shown. For about one-half its length along the central part of the column the vertical hole remains unaltered but from this unaltered part, and with increasing intensity toward either end of the column minute crescentic cracks form on the wall of the hole, along which cracks little fragments of the rock separate and fill the hole more or less completely.

FIG. *d*.—This is a reproduction of a photograph of a thin section cut vertically through the column of Solenhofen limestone of experiment 360. It shows the walls of the vertical hole with the minute cracks referred to in Fig. *c*.

PLATE II

FIG. *a*.—Shows a column of Westerly granite (Exp. 373) which has been submitted to a pressure equivalent to a depth of 25 miles below the surface of the earth for 2½ months. The steel tube has been partially removed exposing the transverse hole, which has been absolutely unaffected by the pressure.

FIG. *b*.—Shows a column of Westerly granite (Exp. 358) which has been exposed to a pressure equivalent to a depth of 35 miles below the surface of the earth, for 2½ months. Under this pressure, as seen, the transverse hole has been filled in. The irregular dark spot, marking the original position of the hole, is caused by the breaking away of a little granite when the steel tube was being removed.

FIG. *c*.—This shows the cracks referred to in the description of Plate I, Figs. *c* and *d;* but they are especially pronounced because in this case (Exp. 384) the steel tube was thinned away about the middle of the column of Solenhofen limestone, permitting the latter to bulge out laterally, thus giving a greater freedom of movement. It was submitted to a pressure of 204,000 lbs. per square inch, equivalent to a depth of rather over 31 miles below the surface of the earth.

ON THE LIMITING STRENGTH OF ROCKS UNDER CONDITIONS OF STRESS EXISTING IN THE EARTH'S INTERIOR

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§ 1. INTRODUCTION

One of the most important problems in geophysics is to obtain a knowledge of the limiting strength of the material forming the solid core of the earth as well as that of the principal rocks forming its crust. According to the modern theory of elasticity the tendency of a solid to rupture is measured by the maximum difference of the greatest and least principal stresses. This criterion first due to Tresca and followed by Sir G. H. Darwin[1] has been found by J. J. Guest[2] to give the best agreement with observed results from experiments on metal tubes subjected to various systems of combined stress. Coulomb's suggestion that the greatest shear produced in a material is a measure of its tendency to rupture leads to a result substantially the same as that given by the hypothesis of maximum stress-difference. This follows from the theorem[3] that the shearing stress at any point is greatest on a plane whose normal lies in the plane of the axes of the algebraically greatest and algebraically least stress and bisects the angle between them, its value being half the algebraic difference between these stress-intensities. The family of surfaces whose tangent planes satisfy the above condition determines the surfaces along which flaws will develop or the material commence to rupture. These surfaces are are called *surfaces of maximum shear*.

The difficulty in the way of the practical application of these criteria lies especially in the determination of the numerical values of the limiting stress-difference for different materials. For the

[1] Darwin, "On the Stresses Produced in the Interior of the Earth by the Weight of Continents and Mountains," *Phil. Trans. Roy. Soc.*, CLXXIII (1882).

[2] Guest, *Phil. Mag.* (Ser. 5), XLVIII (1900).

[3] Minchin, *Statics*, 4th ed., 1889, II, 425.

purposes of ordinary engineering practice, a cube of the material is put into a testing-machine and the stress required to crush the cube is measured. The value of this stress per unit area gives the value of the limiting stress-difference for the material *as long as the boundary conditions are similar to those existing during the test.* Although this condition generally holds in engineering construction work and the criterion is valid, this may by no means be the case when the boundary conditions are very different from those existing in the test, as for instance in the case of rupture in the neighborhood of a cavity or in the case of rupture due to stress-difference deep down in the earth's crust. It has been customary up to the present to employ the crushing test criterion in applications to stresses in the earth's interior.[1] A mathematical analysis of the experiments of Dr. Adams,[2] described in the accompanying paper, throws a great deal of light on the question and can be made to give valuable data on the limiting strength of rocks under conditions of extreme pressure.

It will appear that the crushing test criterion of limiting stress-difference (e.g., 27,000 lbs. per sq. in. for a cubical specimen of Westerly granite of two inches side) is much too low when conditions of stress approach those existing in the earth's interior.

For the purposes of geodynamics, however, "we require to know what is the limiting stress-difference under which a material takes a permanent set or begins to flow rather than the stress-difference under which it breaks; for if the materials of the earth were to begin to flow, the continents would sink down and the sea-bottoms rise up."[3]

A mathematical analysis of tests described in § 4 afford a valuable means of obtaining information on this question.

§ 2. CONDITIONS OF TEST

The tests described by Dr. Adams on the compression of cylindrical rock specimens containing cylindrical cavities and inclosed

[1] Darwin, *loc. cit.*

[2] Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow," see this journal, p. 97.

[3] Darwin, *loc. cit.*

in heavy nickel-steel jackets lend themselves especially well to a determination of stress-differences according to the elastic solid theory. An indeterminate condition which might vitiate the application of analysis to the problem is the state of initial stress brought about by shrinking the nickel-steel jacket over the rock specimen. Since the ends of the specimen are free during this process it is probable that the rock will adapt itself to a state of small initial stress by slight displacements in the direction of the axis. This will especially be the case if some time is allowed to elapse before the test is carried out. Care was taken to make this stress as small as possible under the circumstances; see p. 105.

One of the most serious objections to the application of the theory of elasticity to the determination of conditions of rupture lies in the fact that in most tests the conditions of small strains upon which the theory is based are violated long before rupture takes place. Under the conditions just described the strains remain small in consequence of the very slight yielding of the nickel-steel jacket. It is well known that the elastic constants are only determinate so long as the strains are small and that when the material is stressed beyond a certain limit the rigidity and compressibility take quite different values, so that in most cases the values of the stresses just before rupture cannot be calculated from the conditions of the test. In the present instance, however, by measuring the lateral dilatation of the nickel-steel jacket during a test in the manner described in §4, it is possible to determine how the elastic constants of the rock change in value with stress. In this way it is legitimate to make use of the equations of the elastic solid theory, provided we employ *instantaneous* values of the constants for the specimen and as long as the stresses in the nickel steel do not exceed the limiting stress for that material.

§3. DETERMINATION OF STRESSES IN ROCK CYLINDER UNDER TEST

If we consider the state of stress in the rock specimen and in the nickel-steel jacket as one of plane stress, the problem may be solved without an undue degree of complication. The measurements given in the next section of the lateral dilatation of the nickel-steel jacket when the rock specimen is under pressure show

a considerable bulge of the equatorial diameter, showing that the problem is not strictly one of plane stress. The complete solution of the problem would be of the nature of a similar one considered by Filon[1] in which the state of stress is determined for a cylinder pressed between planes which are in contact with its ends. For the purposes of the present paper, however, we shall deal with the problem as one of plane stress and neglect surface tractions, over the boundary of the cylindrical specimen due to relative displacements of the rock surface and the steel jacket when under pressure. The results will represent to a first approximation the state of stress existing in the rock specimen. From the general solution of the problem given by Love[2] it is an easy matter to calculate the stress-differences at any point of the specimen. According to the usual notation we denote by $\widehat{rr}$, $\widehat{\theta\theta}$, and $\widehat{zz}$ the radial, transverse, and axial stresses respectively: for a case of plane stress there are also the principal stresses. We denote the differences of the principal stresses by the notation

(i) $\widehat{rr}-\widehat{zz}$ (ii) $\widehat{rr}-\widehat{\theta\theta}$ (iii) $\widehat{\theta\theta}-\widehat{zz}$

From the theorem cited in § 1 it is seen that each of the stress-differences (i), (ii), (iii) is associated with a family of surfaces of maximum shear along which the material will crack or flow.

(i) The surfaces of maximum principal shear due to the stress-differences $(\widehat{rr}-\widehat{zz})$ consist of two systems of cones of semi-vertical angle 45° and cutting each other orthogonally. One such system may be imagined to consist of a pile of glass funnels fitting into one another.

(ii) The surfaces of shear due to the stress-differences $(\widehat{rr}-\widehat{\theta\theta})$ consist of two systems of mutually orthogonal cylindrical surfaces whose traces on a plane perpendicular to the axis of the cylinder are equiangular spirals cutting the radii at angles of 45°.

(iii) The stress-differences $(\widehat{\theta\theta}-\widehat{zz})$ give rise to two families of helicoidal surfaces of pitch 45° and intersecting orthogonally. The traces of these surfaces on the surface of the cylinder give rise to helices well known as Luder's lines.

[1] L. N. G. Filon, "On the Elastic Equilibrium of Circular Cylinders under Certain Practical Systems of Load," *Phil. Trans. Roy. Soc.*, CXCVIII A, 1902, 182.

[2] Love, *Elasticity*, 2d ed., 140.

The systems of surfaces of shear corresponding to each of the above cases are shown as (i), (ii), and (iii) in Fig. 1. The cracks developed by failure in each of the above ways as they would appear on the cylindrical surface, over a cross-section perpendicular to the axis and over a section through the axis are represented by the diagrams (i), (ii), and (iii).

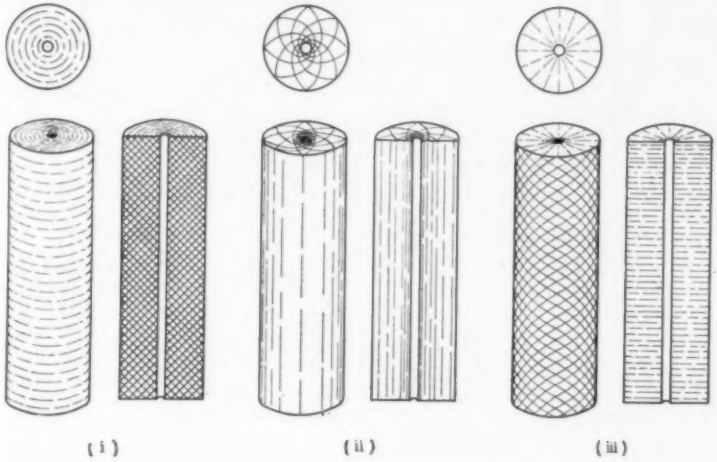

FIG. 1

The surfaces of shear developed in a cylinder under test will depend on which of the stress-differences is a maximum, a condition determined by the elastic constants of the rock and also by the nature of the nickel-steel boundary. As soon as this maximum stress-difference has attained a limiting value characteristic of the material, and determined to some extent by the boundary conditions the corresponding families of surfaces of shear will make their appearance.

Considering first the stresses in the rock specimen, the radial displacement U satisfies the equation

$$\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}+\frac{U}{r}\right)=0,$$

of which the complete primitive is

$$U = Ar + \frac{B}{r}, \tag{1}$$

A and B being constants to be determined from the specified boundary conditions. Longitudinal stress superimposed upon the radial stresses can be taken into account by taking the displacement w in the direction of the axis to be $w = ez$, e being a constant representing a uniform longitudinal extension.

If we denote by $\widehat{rr}$ the stress-component along the radius r, by $\widehat{\theta\theta}$ the component at right angles to r and by $\widehat{zz}$ that along the axis, we find from the stress-equations of equilibrium,

$$\left.\begin{aligned} \widehat{rr} &= (\lambda+2\mu)\frac{\partial U}{\partial r} + \lambda\frac{U}{r} + \lambda\frac{\partial w}{\partial z} \\ \widehat{\theta\theta} &= (\lambda+2\mu)\frac{U}{r} + \lambda\frac{\partial U}{\partial r} + \lambda\frac{\partial w}{\partial z} \\ \widehat{zz} &= (\lambda+2\mu)\frac{\partial w}{\partial z} + \lambda\left(\frac{U}{r} + \frac{\partial U}{\partial r}\right) \end{aligned}\right\} \tag{2}$$

According to Lamé's notation μ is the modulus of rigidity and λ one of the moduli of elasticity such that $\kappa = (\lambda + \frac{2}{3}\mu)$ is the modulus of compression. Poisson's ratio, σ, is denoted by $\sigma = \dfrac{\lambda}{2(\lambda+\mu)}$.

In terms of A and B of equation (1) we have for the principal stresses and the hydrostatic pressure p

$$\left.\begin{aligned} \widehat{rr} &= 2(\lambda+\mu)A - \frac{2\mu}{r^2}B + \lambda e \\ \widehat{\theta\theta} &= 2(\lambda+\mu)A + \frac{2\mu}{r^2}B + \lambda e \\ \widehat{zz} &= 2\lambda A + (\lambda+2\mu)e \\ p &= -\tfrac{1}{3}(\widehat{rr} + \widehat{\theta\theta} + \widehat{zz}) = -\kappa(A+e) \end{aligned}\right\} \tag{3}$$

If accented letters refer to corresponding quantities in the coaxial nickel-steel jacket, we have for the principal stresses a set of equations analogous to (1) and (3),

$$\left.\begin{aligned} U' &= A'r' + B'/r' \\ \widehat{rr}' &= 2(\lambda'+\mu')A' - \frac{2\mu'}{r'^2}B' + \lambda' e' \\ \widehat{\theta\theta}' &= 2(\lambda'+\mu')A' + \frac{2\mu'}{r'^2}B' + \lambda' e' \\ \widehat{zz}' &= 2\lambda' A' + (\lambda'+2\mu')e' \end{aligned}\right\} \quad (4)$$

Let a be the radius of the cylindrical cavity in the rock specimen, b the radius of the specimen, and c the radius of the nickel-steel jacket. The boundary conditions give six equations to determine the constants A, B, e, A', B', e'.

At $r=a$, $\widehat{rr}=0$, giving

$$2(\lambda+\mu)A - 2\mu B/a^2 + \lambda e = 0 \quad (5)$$

At $r=r'=b$, $\widehat{rr}=\widehat{rr}'$, giving

$$2(\lambda+\mu)A - 2\mu B/b^2 + \lambda e = 2(\lambda'+\mu')A' - 2\mu' B'/b^2 + \lambda' e' \quad (6)$$

At $r=r'=b$, $U=U'$, giving

$$Ab + B/b = A'b + B'/b \quad (7)$$

At $r'=c$, $\widehat{rr}=0$, giving

$$2(\lambda'+\mu')A' - 2\mu' B'/c^2 + \lambda' e' = 0 \quad (8)$$

In addition to these we have in the rock specimen, $\widehat{zz}=-P$, where P is the pressure per unit area applied to the end of the test cylinder; this condition gives

$$2\lambda A + (\lambda+2\mu)e = -P \quad (9)$$

Also since the nickel-steel jacket is free from longitudinal stress,

$$\widehat{zz}'=0 \text{ or } 2\lambda' A' + (\lambda'+2\mu')e' = 0 \quad (10)$$

We denote by β the quantity,

$$\beta = \frac{1+\sigma}{1-\sigma}\cdot\frac{\mu}{\mu'}\left\{\left(1+\frac{1-\sigma'}{1+\sigma'}\ \frac{b^2}{c^2}\right)\frac{1-a^2/b^2}{1-b^2/c^2} + \frac{\mu'}{\mu}a^2/b^2\right\}. \quad (11)$$

We then find from the six equations (5) to (10),

$$\left.\begin{aligned} \frac{B}{a^2} &= -\frac{P}{2\mu}\cdot\frac{\sigma}{1-\sigma}\ \frac{1}{1+\beta} \\ \text{and} \qquad e - A &= -\frac{P}{\lambda+2\mu}\left\{1+\frac{\sigma}{1-2\sigma}\ \frac{\beta}{1+\beta}\right\} \end{aligned}\right\} \quad (12)$$

The principal stress-differences in the rock specimen are from (3)

$$\left.\begin{aligned}
&\text{(i)}\quad \widehat{rr}-\widehat{zz}=-2\mu(e-A+B/r^2)\\
&\qquad\qquad =\frac{\sigma}{1-\sigma}P\left\{\frac{1-2\sigma}{\sigma}+\frac{\beta}{1+\beta}+\frac{1}{1+\beta}\ \frac{a^2}{r^2}\right\}\\
&\text{(ii)}\quad \widehat{rr}-\widehat{\theta\theta}=-4\mu B/r^2 \quad =\frac{\sigma}{1-\sigma}P\left\{\frac{2}{1+\beta}\ \frac{a^2}{r^2}\right\}\\
&\text{(iii)}\quad \widehat{\theta\theta}-\widehat{zz}=-2\mu(e-A-B/r^2)\\
&\qquad\qquad =\frac{\sigma}{1-\sigma}P\left\{\frac{1-2\sigma}{\sigma}+\frac{\beta}{1+\beta}-\frac{1}{1+\beta}\ \frac{a^2}{r^2}\right\}
\end{aligned}\right\}\quad (13)$$

The radial displacement U at the outer surface of the rock specimen is given by

$$\frac{U}{b}=\frac{P}{2\mu}\ \frac{\sigma}{1+\sigma}\ \frac{\beta-\dfrac{a^2}{b^2}\ \dfrac{1+\sigma}{1-\sigma}}{1+\beta} \tag{14}$$

and the longitudinal extension per unit length is given by

$$e=-\frac{P}{2\mu}\ \frac{1}{1+\sigma}\ \frac{\beta+\dfrac{(1+\sigma)(1-2\sigma)}{1-\sigma}}{1+\beta} \tag{15}$$

The radial displacement U' at the outer surface of the nickel-steel jacket is given by

$$\frac{U'}{c}=\frac{P}{\mu'}\ \frac{b^2}{c^2}\ \frac{1-a^2/b^2}{1-b^2/c^2}\ \frac{\sigma}{(1-\sigma)(1+\sigma')(1+\beta)} \tag{16}$$

and the longitudinal extension per unit length is given by

$$e=-\sigma'\frac{U'}{c} \tag{17}$$

§ 4. DISCUSSION OF EXPERIMENTAL RESULTS

In order to obtain a numerical verification of the distribution of stress in the rock specimens, measurements of the lateral bulging of the nickel-steel jacket were made by means of a very sensitive Ewing extensometer for a series of increasing loads. The results were obtained for a specimen of Solenhofen limestone in which an axial and transverse cavity had been drilled, and the experiments carried out in the Engineering Testing Laboratory of McGill University.

TABLE I

TABLE GIVING RADIAL DISPLACEMENT OF NICKEL-STEEL JACKET CONTAINING A SPECIMEN OF SOLENHOFEN LIMESTONE UNDER VARYING LOADS

P Pounds per Square Inch	$\frac{U'}{c}\times 10^{-6}$ Radial Displacement at Center	$\frac{U'}{c}\times 10^{-6}$ Radial Displacement over End	Remarks
5,100	0	0	Diameter of nickel-steel jacket 2.5 in., $c=1.25$; length of nickel-steel jacket 3.25 in.
25,500	16	0	
51,000	34	4	Diameter of rock specimen before loading .5005 in., $b=.2502$ in.; length of rock specimen before loading 1.5725 in.
102,000	76	18	
127,000	106	24	*Load removed*, diam. of specimen at ends .5052 in.; diam. of specimen at equator .5030 in.; length 1.5437 in.
153,000	154	38	
175,000	210	46	Diameter of cylindrical cavities .050 inch.
200,000	326	66	*Load removed*, vertical cavity filled with rock powder, horizontal cavity distorted.
5,100	124	38	Longitudinal compression of jacket between 2 in. centers .00003 in., per load of 200,000 pounds. Last reading taken 45 hours after preceding measurement.
1,000	124	38	
1,000	116	37.5	

The nickel-steel jacket used contains about 5 per cent of nickel; the elastic constants of nickel-steel containing $5\frac{1}{2}$ per cent of nickel are taken to be $\mu'=10.8\times 10^6$ pounds per sq. in., $\sigma'=.327$,[1] values not very different from these ordinarily given for steel.

The constants for the Solenhofen limestone of which the rock specimen is made have not been determined; the rock in question resembles in its structure and properties black Belgian marble for which the elastic constants are $\mu=4.33\times 10^6$ pounds per sq. in., $\sigma=.278$.[2]

In calculating the value of β from (11) we may neglect a^2/b^2 and since $b^2/c^2=.04$ we find $\beta=.77$. Equation (16) then gives

$$\frac{U'}{c}=\frac{P(\text{pound per sq. in.})}{1.57\times 10^9} \tag{18}$$

Taking P = 200,000 pounds per sq. in. we have $U'/c=127\times 10^{-6}$.

The observed radial strain over the center of the specimen is considerably greater than this. We may attribute the difference to a diminution of rigidity. Taking as an extreme case $a=0$ and $\mu=0$,

[1] Mercadier, *Comptes Rendus*, 113, 1891.

[2] Adams and Coker, *Elastic Constants of Rocks*, Carnegie Institution, 1906.

$\sigma=\frac{1}{2}$ (incompressible fluid in the nickel-steel jacket), we have $\beta=0$. Then

$$\left(\frac{U'}{c}\right)_{\mu=0}=\frac{P(\text{pounds per sq. in.})}{.345\times 10^{9}}, \tag{19}$$

which gives for $P=200{,}000$ pounds,

$$\left(\frac{U'}{c}\right)_{\mu=0}=578\times 10^{-6}$$

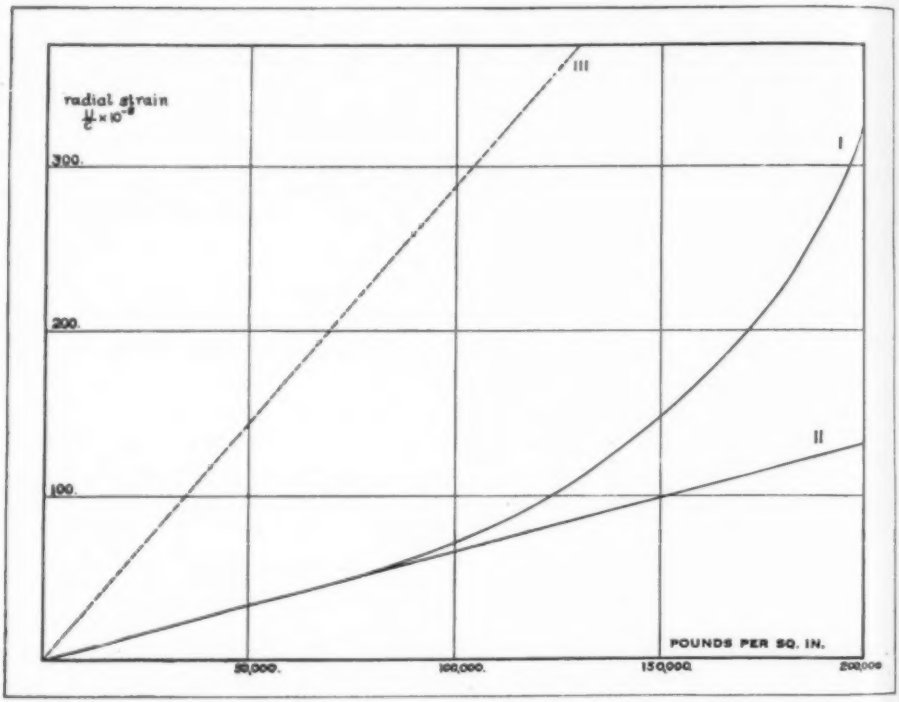

FIG. 2.—Showing relation between radial strain and load for a nickel-steel jacket containing a specimen of Solenhofen limestone under test.

Curve I shows the observed radial strain over the center of the specimen.

Curve II shows the radial strain calculated according to the elastic solid theory for rigidity $\mu=4.33\times 10^{6}$ pound per sq. in. and Poisson's ratio $\sigma=.278$.

Curve III shows the calculated relation between strain and stress for a specimen of zero rigidity.

The results given in Table I are shown graphically in Fig. 2, where the radial strains are plotted on a load base. Equation (16) shows that if the rock specimen had behaved throughout as a perfectly elastic solid, U'/c should be proportional to the load, and the curve connecting load and strain should be a straight line. Even taking into account the equatorial bulge of the nickel-steel jacket the proportionality of strain to stress should be exact on the elastic solid theory.[1] We may interpret the results just obtained to a gradual change in the value of the elastic constants which may be regarded as continuous functions of the stress-differences; in fact, if the departure of Curve I of Fig. 2 from a straight line be attributed to a change in the modulus of rigidity, the variation of the latter with stress-difference might be deduced from an analysis of the curve. The theoretical curve for the radial strain over the center of the specimen agrees well with that observed until a load of 80,000 pounds per sq. in. is reached. A curve for the displacement that would be given if the specimen possessed zero rigidity and a Poisson's ratio of $\frac{1}{2}$ is also shown in the diagram. The departure of the observed curve from that obtained on the hypothesis of perfect elasticity shows that the rigidity modulus diminishes under load and that Poisson's ratio increases toward the limit $\frac{1}{2}$. The observations also indicate that when the load is removed the specimen has received a permanent set with a tendency to recovery with time, showing an indication of elastico-viscous properties.[2] The elastic moduli are also permanently changed; a curious fact explained by this means is that the specimen after having been tested shows a smaller diameter across the center than across the ends, whereas the radial displacement was greatest at that point. Since the displacements were greatest in the central part of the specimen it is reasonable to suppose that the rigidity is permanently altered to a lesser value than in the ends. The result is that when the load is removed the lateral pressure exerted by the nickel-steel jacket is able to produce a greater displacement at the center of the specimen than at the ends, so that a slight waist is produced in the rock cylinder.

[1] Cf. Filon, *loc. cit.*

[2] G. H. Darwin, "On the Bodily Tides of Viscous and Semi-elastic Spheroids," *Phil. Trans. Roy. Soc.*, CLXX, 17.

§ 5. ON THE CONDITIONS OF RUPTURE IN CYCLINDRICAL ROCK SPECIMENS UNDER CONDITIONS OF EXTREME PRESSURE

An examination of equations (13) shows that the stress-differences (i) and (iii) take their maximum values at $r=a$, and that (iii) takes its maximum value at $r=b$. We thus obtain for the maximum values of the stress-differences

$$\left.\begin{aligned} &\text{(i)}\quad \widehat{rr}-\widehat{zz}=P \\ &\text{(ii)}\quad \widehat{rr}-\widehat{\theta\theta}=\frac{\sigma}{1-\sigma}\cdot\frac{2}{1+\beta}\cdot P \\ &\text{(iii)}\quad \widehat{\theta\theta}-\widehat{zz}=P\left\{1-\frac{\sigma}{1-\sigma}\cdot\frac{1}{1+\beta}\left(1+\frac{a^2}{b^2}\right)\right\} \end{aligned}\right\} \tag{20}$$

We note that (i) > (ii) provided $\beta>\frac{3\sigma-1}{1-\sigma}$. Also (i) > (iii) in all cases except when $\beta=\infty$ ($b=c$) in which case (i) = (iii).

Thus if

$$\beta>\frac{3\sigma-1}{1-\sigma}\quad \text{(i)} > \text{(ii) and (i)} > \text{(iii)} \tag{21}$$

so that the specimens will develop the system of surfaces of shear shown in (i) Fig. 1.

$$\text{If } \beta<\frac{3\sigma-1}{1-\sigma} \text{ we have (ii)} > \text{(i)} > \text{(iii)} \tag{22}$$

In this case the system of surfaces of shear described in (ii), Fig. 1, will make their appearance.

In applying the criterion

$$\beta \gtrless \frac{3\sigma-1}{1-\sigma} \tag{23}$$

it is necessary to employ instantaneous values of the elastic constants, since from the previous section these are seen to depend on the load. If from (11) we write approximately $\beta=\frac{\mu}{\mu'}\frac{1+\sigma}{1-\sigma}$ corresponding to $c=\infty$, and $a=0$, the criterion (23) may be written

$$\mu/\mu' \gtrless \frac{3\sigma-1}{1+\sigma}.$$

As long as $\sigma<\frac{1}{3}$ the first of these criteria given in (21) is always satisfied. We have seen, however, that the rigidity μ tends to

diminish with load, while σ tends to the value $\frac{1}{2}$. Under these conditions it is quite possible that the condition $\beta < \frac{3\sigma-1}{1-\sigma}$ given in (22) may be satisfied before the specimen actually begins to rupture in the neighborhood of the cylindrical cavity. The breakdown of a rock specimen under these conditions would be characterized by a tendency to split across a plane through the axis: over a cross-section a system of spiral cracks cutting the cylindrical cavity at an angle would make their appearance and long splinters parallel to the axis would break off from the interior of the cylindrical cavity. Actual cases of fractures of this kind are described by Dr. Adams in the preceding paper.[1] We note that for a solid cylinder ($a=0$) the stress-difference (i) = (iii), so that the conditions for the appearance of the surfaces of shear (i) and (iii) are identical. System (iii) is characterized by the appearance of Luder's lines over the surface of the specimen; these in fact are often observed.

§ 6. ON THE LIMITING STRESS-DIFFERENCE IN THE NEIGHBORHOOD OF A SMALL CYLINDRICAL CAVITY

The preceding analysis may be applied to a determination of the limiting stress-difference S in the neighborhood of the small cylindrical cavities in the specimens of Westerly (Rhode Island) granite tested by Dr. Adams and described in the preceding paper. This granite gave a crushing strength of 27,370 pounds per sq. in. for a two-inch cube. If we note that for this granite $\sigma = .219$,[2] the condition $\beta > \frac{3\sigma-1}{1-\sigma}$ is satisfied and the greatest stress-difference in the specimen is P, so that $S=P$. Experiments 373 and 357 described in Dr. Adams' paper (p. 113) enable a limit to be assigned to the value of S. In experiment 373 a pressure P of 160,000 pounds per sq. in. applied during 75 days produced no change in the diameter of the cylindrical cavity, indicating that no flow or permanent set had taken place. In the case of a similar specimen tested under a pressure P of 200,000 pounds for the same length of time, it was found that the vertical cavity was partly closed up by

[1] Adams, p. 109 of this journal, Plate I, figs. *c* and *d;* Plate II, fig. *c*.

[2] Adams and Coker, *loc. cit.*

rock powder. We are therefore able to assert that for a state of stress at ordinary temperature and lasting for 75 days, S lies between the limits of 160,000 and 200,000 pounds per sq. in., i.e.,

$$160{,}000 < S < 200{,}000 \text{ pounds per sq. in.} \qquad (24)$$

Even at a temperature of 550° C. experiment 381 (p. 115) shows that S is greater than 96,000 pounds per sq. in.

We cannot, however, safely assert that flow or rupture would not take place for a stress-difference less than S if the boundary conditions were very different from these already described at the surface of a cylindrical cavity. In order to settle this point experiments of the type described in § 4 would be required. The value given in (24) for S is very much greater than the limiting stress-difference of 27,000 pounds per sq. in. obtained by means of the usual crushing test. Since this granite is typical of the great mass of igneous rocks which make up the earth's crust, it follows that in geophysical problems which involve a knowledge of limiting stress-difference in the earth's crust, a value considerably higher than that usually employed must be taken.

§ 7. ON THE EXISTENCE OF CAVITIES IN MEDIA UNDER STRESS

(*i*) *State of Stress in the Neighborhood of Cavities in Elastic Media under Shear*

It can be shown that in the neighborhood of both a spherical and a cylindrical cavity, the shear can be nearly equal to twice the shear at a distance.[1] We see therefore that the medium near a cavity will collapse if the stress-difference at a distance exceeds half the limiting stress-difference of the rock material. If the cavity be small this limiting stress-difference may be taken to be the value of S given in equation (24).

(*ii*) *State of Stress in the Neighborhood of a Spherical Cavity in a Medium under Pressure*

If p be the hydrostatic pressure in the medium it can easily be shown from the solution given by Love[2] for a spherical shell under

[1] Love, *Elasticity*, 2d ed., 245. See also a paper by Larmor, *Phil. Mag.* (Ser. 5), XXXIII, 1892, p. 77.

[2] Love, *op. cit.*, 139.

external pressure that the maximum stress-difference in the neighborhood of the cavity is $\frac{3}{2}p$. This result is independent of the elastic constants and of the radius of the cavity. If then the pressure in the medium exceeds $\frac{2}{3}$ the limiting stress-difference of the rock, the cavity will break down. The value of S given in (24) for the limiting stress-differences may be employed provided the radius of the cavity be small.

(*iii*) *On the Stability of a Spherical Cavity in a Medium under Pressure*

That the result quoted in (ii) should be independent of the radius of the cavity seems contrary to experience. The explanation of this anomaly lies in the fact that the question turns on an examination of *stability* rather than on a purely *static* consideration of stress. A problem of a similar kind is that of the collapse of a thin-walled cylinder (e.g. a boiler flue) under external pressure.[1] The result shows that for a cylindrical shell of infinite length collapse will not occur as long as the pressure does not exceed

$$p=\frac{4\mu}{1-\sigma}\left(\frac{t}{a}\right)^3 \qquad (25)$$

where μ and σ denote the rigidity modulus and Poisson's ratio for the material and t/a is the ratio of the thickness to the diameter. The vibrations in the neighborhood of a spherical cavity in an infinite medium under hydrostatic pressure do not appear to have been explicitly worked out; the problem would correspond to the external solution of the problem of the vibrations of a solid elastic sphere.[2] In so far as the stability depends on the radial vibrations of the cavity, a solution could easily be adapted from Poisson's solution for the case of a solid elastic sphere.[3] The result of an investigation on stability would give a result analogous to (25) for a cylindrical shell. When the pressure p is specified the condition of stability will lead to a limiting radius which will be determined by the elastic constants of the medium. A cavity having a greater

[1] Love, *op. cit.*, 530.

[2] Cf. Love, "Gravitational Stability of the Earth," *Phil. Trans.*, 207 A, 1908.

[3] Poisson, "Mémoire sur l'équilibre et le mouvement des corps élastiques," *Mém. Paris Acad.*, t. 8, 1829.

radius than this limiting radius will be unstable and collapse in such a way as to form a number of smaller cavities each of which might be stable.

§ 8. NOTE ON CONDITIONS OF STRESS IN THE EARTH'S CRUST

The determination of conditions of stress existing in the earth's crust constitutes one of the most difficult problems of geodynamics and one on which many recent investigations have been published. If the earth is considered as a perfect sphere in which the density is a function of the radius only, the problem can be solved without difficulty in terms of the elastic solid theory.[1] The application of these results throughout the interior of the earth is not legitimate because an infinite number of laws of density can be formulated to represent the known distribution of mass throughout the earth. Near the surface considerations of surface inequalities vitiate the result. In this connection Love states,[2] "Apart from the difficulty concerning the initial stress in a gravitating body of the size of the earth, a difficulty which we seem unable to avoid without treating the material as incompressible, there is another difficulty in the application of such an analysis to problems concerning compressible gravitating bodies. In the analysis we take account of the attraction of the inequality at the surface, but we neglect the inequalities of the internal attraction which arise from the changes of density in the interior; yet these inequalities of attraction are of the same order of magnitude as the attraction of the surface inequality."

In a recent work Love[3] has attacked the problem of isostatic support of continents and mountains. "The problem admits of an infinite number of solutions even if the distribution of the mass is known. . . . . The problem must remain indeterminate, and all we can do is to obtain explicitly one or more of the infinitely

[1] Lamé solves the problem for an isotropic elastic sphere under its own gravitation (Love, *Elasticity*, 2d ed., 140); the result can only be reconciled with fact by the assumption of incompressibility or by taking into account a state of initial stress. L. M. Hoskins in a paper "Flow and Fracture of Rocks as Related to Structure" (*U.S. Geological Survey*, 1894–95, Part I, 854), solves the problem throughout a compressible concentric crust of uniform density and small thickness; no account is taken, however, of surface inequalities or of considerations of isostasy.

[2] Love, *Elasticity*, 2d ed., 253.

[3] Love, *Some Problems of Geodynamics* (*Adams Prize Essay*, 1911), chaps. ii and iii, p. 12.

numerous solutions. One solution of the problem was obtained by Sir G. Darwin[1] by assuming that the stress is connected with a displacement by the same equations as hold in the ordinary theory of an elastic *incompressible* solid, ... "

The theoretical developments turn on the calculation of stress-differences corresponding to surface inequalities representing continental blocks and mountains. Expressions for the hydrostatic pressure at any depth are not explicitly worked out although it would be possible to calculate from the analysis given the pressure at any depth due to those harmonic inequalities which Love has shown can be made to represent the existing distribution of land and water and the general form of continental blocks. For most purposes it is sufficient to calculate the pressure at any depth as that due to the weight of the corresponding column of rock: this formula gives a value of greater relative accuracy the greater the depth at which the pressure is calculated.

§ 9. DEPTH AT WHICH CAVITIES CAN EXIST

(*i*) *Collapse Due to Stress-Differences in the Earth's Crust*

Love[2] shows that on the isostatic theory the maximum stress-difference due to a harmonic inequality of the third order representing a continental block of maximum elevation 2 kms. is approximately the weight of a column of rock equal to 0.0208 of this greatest height, i.e., about 0.0114 of a metric tonne per sq. cm. (162 pounds per sq. in.). This value is greater than that brought about by inequalities of the first and second order. The stress-difference is also worked out for a parallel series of mountain ranges 400 kilometers apart and having a height of 4 kms. from crest to valley-bottom; it is shown that the greatest value of the stress-difference is about .26 metric tonnes per sq. cm. (3,700 pounds per sq. in.). In both cases the stress-difference is very much less than $\frac{1}{2}S$ so that no state of stress-difference due to weights of continents or mountains is intense enough to cause the material of the earth's crust to rupture in the neighborhood of a small cavity.

[1] Darwin, "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains," *Phil. Trans. Roy. Soc.*, CLXXIII (1882).

[2] Love, *op. cit.*, 36; also 47.

No account is here taken of stress-difference brought about by the folding of the earth's crust or that due to residual effects of a state of very intense stress which may have been brought into existence at a very remote period of the earth's history.

(ii) Collapse Due to Pressure in the Earth's Crust

We have noticed in § 8 that the pressure at any point of the earth's crust may be roughly represented by the weight of a column of rock of that depth. If w represent the average weight of rock at the earth's surface per cubic cm. and h the depth in cms., a small spherical cavity can exist provided

$$wh < \tfrac{2}{3}S \qquad (26)$$

where S is the limiting stress-difference of § 6 expressed in grammes per sq. cm. Making use of the numerical values corresponding to a limiting stress-difference between 160,000 and 200,000 pounds per sq. in. (1.13×10^6 and 1.41×10^6 grammes per sq. cm.) for Westerly granite and taking 2.7 as the mean density of surface rocks, we can assert that small cavities in the earth's crust will not collapse provided the depth does not exceed a quantity h whose value lies between 27.7 and 33.7 kilometers (h between 17.2 and 20.9 miles). This estimate is several times greater than that deduced by Hoskins,[1] the reason being that it is necessary to make use of a very much higher value of limiting stress-difference than that employed in the investigation referred to. Even at a temperature of 550° C. which is supposed to exist at a point 11 miles below the earth's surface, Adams has shown that S is greater than 95,000 pounds per sq. in. which corresponds to a depth of 15 miles. Any internal pressure in the cavity (due to water-pressure, steam, etc.) would increase the above estimate for the depths at which cavities can exist.

The *size* of a cavity which can exist at a given depth depends on considerations of *stability* and would demand a separate investigation.

[1] Hoskins, *op. cit.*, 859. Hoskins expresses the result of his investigation in the form "cavities must certainly close up if $wh > S$." The value for S is taken to be 25,000 pounds per sq. in. The much higher value between 160,000 and 200,000 pounds per sq. in. indicated by experiments on Westerly granite shows that Hoskins' estimate for the depth at which cavities must close, must be increased between 7 and 8 times.

§ 10. SUMMARY AND CONCLUSIONS

1. Secs. 1 to 3 are devoted to a mathematical discussion of the state of stress existing in cylindrical rock specimens incased in heavy nickel-steel jackets and described by Dr. Adams in an accompanying paper.

2. In sec. 4 it is shown that observations on the radial strains of the nickel-steel jacket agree well with the calculated values as long as the load does not exceed a certain value; beyond that point the results of experiment indicate a change in the elastic constants with load; an analysis of observations of this type could be made to give a relation between the rigidity and the load for stress-differences beyond the elastic limit. The results of sections 4 and 5 also give a good account of the manner in which the rock specimens break down under load.

3. The experimental results of Dr. Adams discussed in sec. 6 of the present paper show that in the neighborhood of a small cylindrical cavity, in a specimen of Westerly granite, no flow or set takes place when the stress-difference amounts to as much as 160,000 pounds per sq. in. The cavity just begins to break down for a stress-difference of 200,000 pounds per sq. in. We therefore assign to the limiting stress-difference in the neighborhood of small cavities in rocks typical of that forming the greater part of the earth's crust, a value S between 160,000 and 200,000 pounds per sq. in. for ordinary temperatures.

4. Secs. 7 to 9 deal with the existence of cavities in media under stress with especial reference to the depth at which cavities in the earth's crust can remain open.

It is shown that no state of shearing stress in the crust of the earth, due to the weights of continents and mountains can cause the collapse of the rock in the neighborhood of a small cavity.

It is also shown that as far as hydrostatic pressure in the earth's crust is concerned a small cavity at ordinary temperatures will remain open provided the depth does not exceed a value between 17.2 and 20.9 miles. At a temperature of 550° C. supposed to exist 11 miles below the earth's surface, cavities will remain open when submitted to considerably greater pressures than are found at this depth. These values greatly exceed previous estimates because

experiment shows that a much higher value of limiting stress-difference than that usually employed must be taken in the neighborhood of small cavities.

5. The *size* of a cavity which can exist at a given depth depends on considerations of *stability* and would demand a separate investigation.

January 30, 1912

AN OLD EROSION SURFACE IN IDAHO: ITS AGE AND VALUE AS A DATUM PLANE[1]

JOSEPH B. UMPLEBY

THE EROSION SURFACE
Evidences of a Former Erosion Cycle
Correlation and Extent
Elevation and Preservation
AGE OF THE SURFACE
Evidence from Within the Area
Evidence from Nearby Areas
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SUMMARY

THE EROSION SURFACE

Evidences of a former erosion cycle.—A plateau surface has long been recognized in Idaho, and over much of the state it has been described as a feature of erosion. The observations of the writer have been confined to an area of about 5,000 square miles in the eastern part of that great highland mass known as the Salmon River Mountains, but the literature shows that a description of this area is applicable to much of the state.

The Salmon River Mountains are characterized by deep canyons separated by even-crested divides, which here and there widen out into broad flats. Within the region there is not only a striking accordance of summit levels; there is a general continuity of level summit areas. Plateau remnants several square miles in extent are not uncommon. One of these is Poverty Flat near Challis in Custer County. It is a comparatively level tract of about 25 square miles, and occurs at an elevation 9,600 feet above sea (Fig. 1). Bordering it are narrow valleys as much as 5,000 feet deep, but beyond them high, even-crested ridges and occasionally flat areas continue to the horizon in every direction. The rocks forming this flat are steeply tilted schists, slates, and quartzites, the latter

[1] Published by permission of the Director of the U.S. Geological Survey.

here and there forming low hills. Near Leesburg, in Lemhi County the plateau surface is also well preserved. Here it is about 8,500 feet in elevation, and breaks off abruptly along the canyon of Salmon River, which flows in a gorge 5,500 feet deep.

Equally significant with the high flat-topped areas are the innumerable level-crested divides which extend out from them, and with other more isolated summits form a veritable labyrinth of highland tracts. Also worthy of note, as indicating that streams once flowed near the summit levels, are occasional rock-cut terraces which parallel the plateau surface but at slightly lower

FIG. 1.—A portion of Poverty Flat, which has an elevation of 9,600 feet, and is bordered by canyons as much as 5,000 feet deep. The spur on the right shows the highly inclined beds across which the flat is developed.

levels. One of these occurs along the west side of Spring Mountain, and another along the south side of Poverty Flat.

These several features clearly indicate a plateau surface, now deeply dissected, and when it is remembered that it is cut across highly inclined rocks of diverse composition, it seems equally clear that it could only have been developed by profound erosion. The region was reduced to gentle relief, and later raised to its present elevation.

Correlation and extent.—Mr. Lindgren describes the same surface in west-central Idaho, and concludes that[1] "The whole mountain region should probably be regarded as a vast plateau. . . . . The uplift of this plateau and its intricate and deeply cut drainage system evidently antedate the Miocene period." These high-

[1] Waldemar Lindgren, *Twentieth Annual Rept., U.S. Geol. Surv.*, Pt. III (1900), 77.

lands extend to the north, and in speaking of them the same writer says:[1] "Their combined crest-line would form an undulating plain differing little in elevation in the various parts of the Clearwater Mountains. From their westerly margins the mountains slope rapidly to the lava plateau, which has an elevation of 3,000 to 3,500 feet. . . . . Along Salmon River the high mountain plateau extends farther westward, and its last ramparts overlook the great bend of that river, rising 6,500 feet above its water line." Mr. Lindgren's conclusion is that "We must regard this surface as the result of erosion. The country was worn down to a comparatively gentle topographic feature, then uplifted and deeply dissected by canyons."

Mr. Calkins[2] describes the Coeur d'Alene Range, still farther north, as having a "general aspect similar to that of a maturely dissected plateau." He describes also the Cabinet and Purcell ranges in western Montana, in similar terms. East of these, Mr. Willis[3] recognized a peneplain over the Galton Range, and suggests that it may continue eastward over the Livingston and Lewis ranges. Northward in British Columbia the Interior Plateau is described by G. M. Dawson[4] as an elevated peneplain of Eocene age. South of this the writer[5] recognized what was thought to be the same surface at Republic, Washington.

The extent of the old erosioned surface can only be outlined in a general way because of the many localities where its identity has been destroyed and the broad areas which have not been studied physiographically. The above citations show, however, that a plateau surface cut across greatly disturbed beds extends over much of Idaho and into adjoining parts of Montana, Washington, and British Columbia. The areas in Idaho are continuous; those elsewhere are more isolated, but that all date from the same cycle of erosion will appear rather obvious during the later discussion.

Elevation and preservation.—The combined crest lines of the plateau areas in Idaho would form an undulating plain which

[1] Waldemar Lindgren, *P. P. 27, U.S. Geol. Surv.* (1904), 14.

[2] F. C. Calkins, and D. F. MacDonald, *Bull.* 384, *U.S. Geol. Surv.* (1909), 14, 19.

[3] Bailey Willis, *Geol. Soc. Amer.*, XII (1901), 349.

[4] G. M. Dawson, *Trans. Royal Soc. Canada* (1890), 13.

[5] J. B. Umpleby, *Wash. Geol. Survey, Bull. I* (1910), 11.

reaches its maximum elevation of about 10,000 feet along a course through Gilmore and Challis. Northwestward it grades off to 8,500 feet in the north part of Lemhi County, and thence to about 7,000 feet in the Clearwater Mountains. This elevation is also common in northwest Montana, but westward in the Colville Mountains and on north in the Interior Plateau the summits are about 5,000 feet above sea.

Faulting and folding have affected the plateau area of central and eastern Idaho since its last elevation, but through all, the integrity of the old surface has persisted in a remarkable degree. Local prominences above the general level, though not characteristic of the region, occur. Some of these are undoubtedly erosion remnants, but others probably involve faulting, and some may be due to folding. In western Montana the old surface appears from the literature to be far less perfectly preserved. In northeastern Washington and in British Columbia it is also preserved imperfectly. Here there is a remarkable accordance of summit levels, but no large plateau remnants, such as those in Idaho, have been described.

Age of the Surface

Evidence from the area.—After the last general elevation of the region great valleys were developed, and in these extensive lake beds accumulated during the Miocene period. Such deposits occur at Salmon, Idaho,[1] in western Montana,[2] at Republic, Washington,[3] and at various places in the Interior Plateau of British Columbia.[4]

Allowing the Oligocene for the development of the broad valleys occupied by the Miocene lake beds, the old erosion surface is pre-Oligocene. On the other hand, it cuts all the older formations of the region including the granite, which is post-Triassic. Thus from evidence within the plateau region the old erosion surface is pre-Oligocene and post-Triassic.

[1] J. B. Umpleby, *Bull. U.S. Geol. Surv.* (now in manuscript).

[2] Earl Douglass, *Mont. Univ. Missoula, Mont.*, 27 pp., 4 plates, 1899; *Carnegie Mus. Annals*, V (1909), 159-65.

[3] J. B. Umpleby, *Bull. I, Wash. Geol. Surv.* (1910), 11.

[4] G. M. Dawson, *Trans. Royal Soc. Canada* (1890), 14.

Evidence from nearby areas.—It is thought that adjoining regions afford further evidence as to the age of this surface. Extensive deposition is a corollary of profound erosion, hence we should expect to find a sedimentary record of the cycle of erosion represented by the present plateau surface. The Rocky Mountain

FIG. 2.—The figure illustrates the distribution of Eocene sediments in the Northwest. The horizontal lines indicate areas which have been described as of the plateau type. The area of vertical lines is similar but is based on oral communications. Adapted from the Geologic Map of North America, with the plateau areas added.

region is known to have supplied vast volumes of sediments during the Cretaceous, but not until the Eocene does the distribution of sediments bear a significant relation to the present plateau area. Fig. 2 illustrates the distribution of the Eocene sediments in the

Northwest and the parallel lines of the same figures show the position of the areas described as representing the plateau type. The distribution of Eocene sediments around these areas strongly suggests a relation between the two. It seems that the sediments could not have been derived from the region after its last elevation for two reasons: (1) It is very doubtful if the plateau is sufficiently dissected to afford the volume of material represented by the Eocene beds, and (2) All the more important valleys of the area drain westward, and in all probability have done so throughout their entire history. This is true of the Rocky Mountain trough, the Purcell trough, and the Snake, Salmon, and Columbia river channels. These, together with their tributaries, represent perhaps 90 per cent of the present dissection of the plateau region. If we assume that the old erosion surface is pre-Eocene the material derived from these several valleys may be thought to account for the narrow fringe of Eocene sediments on the west, but cannot account for the incomparably more extensive Eocene beds which lie to the east of the present plateau region.

Conclusion.—From this line of evidence it is concluded that the Eocene sediments were derived from the plateau area during that great cycle of erosion which resulted in a comparatively level surface, and therefore that the plateau region of the present day was characterized by gentle topographic features at about the close of the Eocene period. Whether or not that former great cycle of erosion began with the Eocene may be an open question, but that it closed with the Eocene, and therefore that the present plateau surface is of Eocene age, there seems to be little room for doubt.

The Eocene Surface as a Datum Plane

Over much of Idaho no satisfactory datum plane has been recognized between the Algonkian and the Pleistocene. In the southeastern part of the State formations of Paleozoic age are present and along the western side are the great sheets of Miocene basalt. Other datum planes are recognized, but they are all well removed from the plateau area. Thus where a datum plane is most needed the Eocene erosion surface is best preserved.

The value of this surface in time determinations is perhaps greatest in dating the ore deposits of the plateau region. Two distinct periods of mineralization are recognized in this area. The earlier deposits are cut by the Eocene surface, but the later are inclosed in or associated with eruptive rocks which fill valleys developed after its elevation. Thus the Eocene surface was developed during the interval between two great periods of mineralization. Reasoning from it as a datum plane the deposits may be rather definitely placed in time. On the one hand is the Pleistocene glaciation and the amount of erosion which preceded it but followed the veins, thus placing a fairly definite limit. On the other the granite, which is older than the earlier veins, is assigned to the latest Cretaceous or earliest Eocene as brought out in the next section.

Age of Granitic Intrusions Suggested by the Eocene Surface

There are many granitic batholiths within the plateau region. The largest of these is the one in central Idaho, which is more than 20,000 square miles in extent. Several others approach to or exceed 1,000 square miles in area, and those of smaller size are to be numbered by the score. Indeed, probably one-third of the surface rock throughout the present plateau region is granite or closely allied batholithic types. Both broadly and locally these intrusions vary from normal granite through soda granite and quartz-monzonite to quartz-diorite. Their distribution is shown by Fig. 3. A comparison of this with Fig. 2 brings out the striking accordance in distribution between the area of granitic intrusions and the plateau. Their coextent suggests a genetic relation between them, but the granite constitutes a larger part of the plateau surface; hence, if a relation exists it must date from the earlier part of the erosion cycle during which the Eocene surface was developed. The problem, therefore, is to show whether the granite entered at this or at a still earlier time. Probably most geologists will agree in the opinion that such a tremendous volume of magmatic material did not enter beneath the region without causing or accompanying a profound elevation of the

surface; yet the area of granitic intrusions does not show a significant relation to surrounding sedimentary deposits until the Eocene. It is believed, therefore, that the granite intrusions accompanied the elevation which initiated that great cycle of erosion which

FIG. 3.—The figure shows the distribution of granitic rocks in the plateau region. Adapted from the Geologic Map of North America.

resulted in the Eocene surface. The granite batholiths of the plateau region therefore are assigned to the late Cretaceous or early Eocene.[1]

[1] Since this article was prepared, Mr. Adolph Knopf has told the writer that during recent field work he found the Butte granite to cut andesites which should probably be correlated with the Livingston formations. Mr. F. C. Calkins also has found the granite intrusions of the Phillipsburg quadrangle, Mont., to be post-Colorado. Thus recent geologic studies support conclusions and suggestions herein set forth.

Summary

The principal problems discussed in this paper fall under four headings, as follows:

1. An old erosion surface which may prove to be a peneplain, but which because of inadequate study is not so defined here, extends over much of Idaho and into adjoining parts of Montana, Washington, and British Columbia.

2. The surface is assigned to the Eocene because of the relation of Miocene lake beds to it and because of its relation to Eocene deposits.

3. The Eocene surface forms a valuable datum plane in broad areas where time relations between the Algonkian and the Pleistocene are otherwise obscure.

4. It is suggested that the great granitic batholiths of the plateau region either initiated or accompanied the initiation of the cycle of erosion which resulted in the Eocene surface and hence, that they are of late Cretaceous or early Eocene age.

EUGEN HUSSAK

MIGUEL A. LISBOA[1]

Professor Eugen Hussak died in a little hotel in the city of Caldas in southern Minas Geraes, Brazil, on the fifth of September last. The important part he took in the development of mineralogy and petrography in Brazil, his standing among specialists, and his scientific attainments call for a fuller account of his life and labors than we are able to give at the present.

Francis Eugen Hussak was born at Wilden, Steiermark, Austria, March 10, 1856. His parents were Johann Hussak, a lawyer, and his wife Therese von Wagner. After he came to Brazil he married Herminia Hennies by whom he had two sons. He was educated in the Gymnasium and University of Gratz, studied afterward at the University of Leipzig, where he was a pupil of Ferdinand Zirkel, one of the founders of the modern science of petrography, and later returned to Gratz where he took his Doctor's degree. While working under Zirkel at Leipzig, Hussak began the microscopic study of minerals and rocks, and it was from him that he received his greatest inspiration and encouragement. After graduation he went to Vienna where he attended the lectures of Tschermak, and was for three years engaged on the K.K. Geolog. Reichsanstalt. In Vienna he prepared his book *Anleitung zur Bestimmung der gesteinsbildenden Mineralien* which was published at Leipzig in 1885, a book that was translated into English by Professor E. G. Smith, and was published in the United States in

EUGEN HUSSAK

[1] Translated from the Portuguese by J. C. Branner. The original article appeared in the *Jornal do Commercio*, Rio de Janeiro, October 7, 1911.

1893 under the title of *The Determination of Rock-forming Minerals*. He was then called to Germany as assistant to Professor D. Laspeyres and in that capacity worked at Kiel and later at Bonn. He remained in Germany until 1887, publishing in the meantime his *Katechismus der Mineralogie*, a book which has passed through five editions.

In the universities and museums of Germany and Austria Hussak had examined various collections of Brazilian rocks and minerals that had been put aside to await classification. At Vienna he saw the collections made by Helmreichen, in Bonn he saw those made by Krantz, and at Berlin he saw a collection from Rio Grande do Sul. In all these collections he saw much interesting material, and Brazil seemed to him a new land of promise. But Hussak was not a man who cared to work over the ground or materials left by others, and he took no pleasure in finding fault with the work of others. He preferred new fields. Brazil offered such an opening and whether and when he would go there was only a question of opportunity. He chanced to have as one of his pupils at Bonn a young Brazilian named Jordano Machado. A collection of nephelene rocks taken from a railway tunnel on the Mogyana Railway near the city of Caldas had been sent Jordano Machado, and he had chosen the collection for the subject of his thesis. Hussak looked after the preparation and publication of this paper with great care and interest. Every one of the microscopic rock slides was examined by him personally and carefully. The thesis of Jordano Machado was a brilliant success, but the young petrographer eventually gave up his petrographic work in order to raise coffee.

At this point Hussak left his professorship in the university and went to Brazil with his pupil, who extended to him the cordial Brazilian hospitality of his father's coffee plantation. His early experiences in Brazil were rather trying. On the coffee plantation there was really nothing for a mineralogist to do. Besides there he had no outfit for such work; he lacked microscope, slides, laboratory, and all. After some months of this he felt that he must return to Germany; but unfortunately he had not even the means for the voyage.

In the palace of Dom Pedro II, the emperor of Brazil, he found a temporary solution of the problem. Someone told the emperor that a mineralogist whom Rosenbusch spoke of very highly was in the country without occupation. This led to his being engaged to give instruction in mineralogy and petrography to Dom Pedro de Saxe, the emperor's grandson. But the lessons were soon interrupted. The pupil wanted to get on too fast. Dom Pedro de Saxe wanted to begin his studies by the publication of original papers. His Austrian instructor coolly told him that it was too early yet; that one should learn before he began to teach. The young prince was offended; the teacher insisted, and the matter ended with his being shown the door.

Hussak was living at that time at the old Beresford Hotel in Petropolis in front of the imperial residence. He went to his rooms and began preparations for leaving the city that same day. He was a simple man, and in the crises of life he was at times a mere child. He frankly told the keeper of the hotel of his humiliation, and of his financial difficulties. The hotel-keeper was more philosophical about the matter; he consoled the professor, but did not allow him to leave.

The next morning Dr. Stoltz knocked at Hussak's door, bringing an invitation from the magnanimous emperor for him to appear at the palace. Hussak went at once, and if any apologies were lacking from the young prince they were more than made up by his Imperial Majesty himself. So the lessons were continued for a while at least.

Later O. A. Derby engaged Hussak on the geological survey of the state of S. Paulo, and for twenty years he was the leading petrographer of Brazil.

A glance at the bibliography of Eugen Hussak shows a remarkable originality in his work. To be sure, the backward condition of petrographic geology in Brazil contributed largely to this originality. Mineralogy and petrography were sciences but little cultivated among us. Such work had been begun here by Gorceix in the School of Mines at Ouro Preto, but when the Austrian professor came to S. Paulo there was really no one in the country who was acquainted with the details of the technique of modern petro-

graphy. In S. Paulo there came together, by accident it may be said, a geologist, a petrographic mineralogist, and a chemist, each of them a leader in his specialty. These men were Derby, Hussak, and Florence. They were to work together, and each was to place at the disposal of the others the resources of his own science.

It may be said of Hussak that all his works were contributions to science. He described a large number of new minerals, notably, brazilite, lewisite, zirkelite, tripuhyte, derbylite, senaite, florencite, chalmersite, and gorceixite. He also pointed out various mineral substances of economic importance, such as oxide of zirconium at Caldas, platinum in Minas, carbonados and diamonds in S. Paulo, corundum in Brazil and in Uruguay, and likewise cassiterite, monazite, and several others.

On mineral deposits he left two noteworthy contributions. These were his studies of the gold-bearing beds of Passagem, and on the occurrence of palladium and platinum in Brazil. When he made this last investigation, he wrote to Russian geologists who had sent him materials from the Ural region, calling their attention to certain facts that had hitherto escaped their notice. He began the systematic study of the heavy minerals of the diamond-bearing gravels and added much to the work that had been done by Gorceix. On this subject he has left much valuable material unpublished.

Many years ago he began the preparation of a mineralogy of Brazil, and from the large amount of original matter published by him on this subject, from the many unpublished observations that he had put aside for this work, and from the ability he showed in the preparation of a book for instruction, it is evident that such a volume would have embraced all of his work as a mineralogist. Unfortunately this important work is lost with him.

Wherever he was known he has left sincere friends. In Brazil he leaves no successor.

THE PETROGRAPHIC CHARACTER OF OHIO SANDS WITH RELATION TO THEIR ORIGIN[1]

D. DALE CONDIT
Geological Survey of Ohio, Columbus

In connection with a report in preparation by the Geological Survey of Ohio on glass and molding sand, a petrographic examination of a large number of samples was made by the writer of this paper. The samples were collected from all parts of Ohio and represent practically all the important deposits of the state from the oldest to the very recent. About ninety rock samples, Carboniferous and older, were examined, and forty uncemented, recent sands from the glacial drift and other sources. The petrographic work was done in the geological laboratories at Columbia University.

In preparing the samples for inspection with the microscope, thin sections were made of the rocks. Most of these had only a slight bond so they were first boiled in Canada balsam until all the interstices were permeated by that liquid. On cooling there resulted a firmly cemented mass which would permit of grinding to the usual thickness. In the case of loose, uncemented sands, liquid mounts were made in oil of cloves which has an index refraction similar to that of balsam. Many of the samples being made up of grains too thick for study with polarized light were first crushed to 100-mesh size in an agate mortar, after a preliminary inspection had been made to determine the shape and size of grain.

The sands ordinarily met with in Ohio may be divided into three great groups on the basis of physical properties and mineral make-up. The three groups are: (1) The old sandstone formations Permo-Carboniferous and older; (2) residuary and outwash deposits derived by weathering and erosion of the sandstones; (3) glacial drift sands—recent deposits made up of assorted material

[1] Published with permission of the State Geologist of Ohio.

obtained from the drift by the action of wind and water currents. Each group has certain physical and mineralogical features which are quite characteristic of the sand wherever found and which will be described.

The old sandstones of Group 1 are made up of travel-rounded grains cemented more or less firmly by silica, limonite, hematite, or some other bond. Quartz is by far the most abundant mineral. The accessory constituents seldom make as much as 15 per cent of the sand. They are minerals of a rather stable nature together with secondary products derived from the decompositon of the less stable original minerals. Orthoclase and plagioclase are as a rule much decomposed and their presence is shown by aggregates of sericite, kaolinite, and secondary quartz. Occasionally plagioclase grains are seen which still show twinning lines. Microcline is almost invariably fresh and unaltered. Tourmaline is common. Muscovite is widely distributed, being found in nearly every sand, but biotite is rare. Amphibole and pyroxene are almost entirely altered to chlorite, limonite, and other secondary products. No garnet was found in any of the sandstone samples. A sand from the Sharon Conglomerate of Summit County is regarded as representative of the group and its mineral list follows. The minerals are listed in order of abundance.

1. Quartz
2. Muscovite
3. Kaolinite
4. Microcline
5. Zircon
6. Limonite
7. Orthoclase
8. Plagioclase
9. Sericite
10. Hematite
11. Apatite
12. Chlorite
13. Rutile

There is a slight bond of sericitic kaolinite and limonite. Some of the quartz grains show slight secondary growth. The feldspars are almost entirely altered and their outline is preserved by aggregates of sericite, kaolinite, and secondary quartz which are so interlocked as to resemble a mosaic pattern.

The Sylvania (Silurian) formation of northwestern Ohio is a good illustration of a very pure sand having few accessory minerals. A sample from Lucas County was found to contain only quartz,

calcite, dolomite, rutile, and apatite. The calcite and dolomite occur as minute rhombohedrons which serve as a cementing material. The rutile and apatite are needle-like inclusions in the quartz. The quartz grains average about 0.3 mm. in diameter and are nearly spherical in outline. A chemical analysis shows 95.11 per cent of silica.

There is a number of secondary minerals which have found place in the old sandstones of Ohio subsequent to their deposition. Some of these have resulted from decomposition in place of original minerals while others have been brought in from foreign sources and precipitated from solution. Some of the secondary minerals due to precipitation from solution are: secondary quartz, hematite, limonite, calcite, dolomite, siderite, pyrite, and marcasite. Some of the alteration products of original minerals are: kaolinite, sericite, chlorite, secondary quartz, leucoxene, limonite, and hematite.

The sands of Group 2, derived by weathering and erosion of the old sandstones, are usually loose, uncemented deposits that occur as a residuary mantle on the upland or as bar deposits along ancient and modern valleys. Such sands may be made up of rather angular grains, especially if there was silicification of the sandstone whose weathering furnished the material. A coating of iron oxide on the grains is quite characteristic. This may be so thick as entirely to conceal the interference colors of the quartz when viewed under crossed nicols. The minerals of residual sands are fewer than those in the original sandstone. Solution and erosion incident to weathering eliminate many of the accessory constituents and as a result minerals other than quartz and limonite are few. Such materials when favorably situated might be reworked by wind and water currents to form very pure quartz sand deposits comparable with the Sylvania.

So much of Ohio is covered by glacial drift that most of the modern river sands are a mixture of contributions from local sources and from the drift. There are, however, a few counties in the southeastern part of the state which have sand deposits obtained entirely from local sandstones with no contributions from the glacial drift. These deposits are found along both modern and

pre-Glacial drainage channels. In Gallia County is an ancient, abandoned valley which forms a prominent topographic feature and has been traced for many miles by Tight,[1] who has named it the Marietta River. A sand sample taken from a bar deposit in this valley has the following mineral make-up: quartz, limonite, zircon, tourmaline, apatite, and kaolinite. All of the grains are thickly coated with limonite.

The sands of Group 3, derived by assortment of the Glacial drift, are usually of a very heterogeneous nature both as to shape of grain and mineral composition. There are sharp, angular particles with freshly fractured surfaces that have evidently resulted from the crushing and granulation of rock masses. There are also well-rounded grains that represent sand deposits in the path of the advancing ice front which were carried along and blended with the comminuted rock material. During the recession of the ice and subsequently, wind and water currents have assorted much of the drift into gravels, sands, and silts. In the northern part of the state are fine-grained sands and silts that have been deposited in the shallow waters of recessional lakes. These sands are remarkably well assorted. Extensive deposits in Erie County are found suitable for molding sands. In one sample the diameter of grain was found to range between 0.3 and 0.06 mm. with 0.1 mm. as an average. Only the largest grains show any rounding. Another sample was made up of sharp grains ranging from 0.05 mm. down to mineral flour.

As to mineral content the glacial drift sand is quite distinct from the preceding groups. Quartz is still the most abundant mineral, but there is almost always a high percentage of accessory minerals. Many of these are of a perishable nature and cannot withstand solution and decomposition incident to long weathering. Outcrops of crystalline metamorphic rocks beyond the Great Lakes may be regarded as the source of such minerals. Probably 90 per cent of the drift in any one locality is made up of materials derived from within fifty miles of that point but there is quite invariably a

[1] W. G. Tight, "Drainage modifications in southeastern Ohio and adjacent parts of West Virginia and Kentucky," *Professional Paper U.S. Geol. Surv. No. 13*, p. 76; also Plate XI.

portion which, by its mineral content, shows derivation from the crystalline rocks. A number of minerals entirely wanting in the old sandstones are found fresh and little altered. Garnet, diopside, augite, enstatite, hypersthene, hornblende, actinolite, cyanite, and free grains of magnetite are abundant in the drift. Of these garnet, diopside, augite, enstatite, hypersthene, and cyanite are not found in the old sandstones and the others are rare. The former presence of abundant ferromagnesian minerals is indicated by chlorite, saussurite, and other alteration products.

The character of the glacial sand type is well shown by a fine-grained sand from near Sandusky, Ohio. The bed is regarded as an off-shore deposit in Lake Warren.[1]

MINERALS IN ORDER OF ABUNDANCE

1. Quartz
2. Garnet
3. Diopside
4. Hornblende
5. Enstatite
6. Microcline
7. Plagioclase
8. Orthoclase
9. Hypersthene
10. Tourmaline
11. Zircon
12. Limonite
13. Kaolinite
14. Apatite
15. Sericite
16. Epidote
17. Magnetite
18. Rutile

The sand is made up of angular grains with surfaces that show recent fracture. The size grades from 0.05 mm. diameter down to mineral dust. There is little limonite coating on the grains. Garnet, diopside, enstatite, hypersthene, hornblende, and feldspars are the principal accessory minerals and none of these are much decomposed.

The characters of the three great sand types may be summarized as follows: The rock sands (all Paleozoic) are made up of travel-rounded grains more or less firmly cemented. The minerals are those of a stable nature together with some which have been derived by the alteration of less stable original minerals. Ferromagnesian minerals are almost entirely wanting. The residual sands and outwash deposits derived from erosion of the sandstones are made up of products that represent the final

[1] Frank Leverett, Monograph 41, *U.S. Geol. Surv.*, Plate XXII.

results of weathering. Many minerals present in the sandstones have been eliminated and there remains little besides the quartz, which is itself usually heavily coated with limonite. The glacial drift sand is a hodgepodge mixture of anything that happened to be in the path of the ice. Travel-rounded grains derived from sand deposits are mixed with sharp particles produced by the comminution of rock. Minerals of an unstable nature recently derived from the crystalline rocks are abundant and these show little alteration.

MINERAL SUMMARY

Thirty-four minerals have been recognized in Ohio sands. Some of these are abundant in practically every sample while others are less widely distributed and are only present in small amounts. While the samples were taken from all parts of the state from sands of all ages they can hardly be regarded as representative of many of the formations because only those outcrops which appeared suitable for glass or molding were sampled. A list of the minerals is given with notes as to the occurrence of each.

MINERALS OF OHIO SANDS

Quartz	Garnet
Orthoclase	Corundum
Plagioclase	Magnetite
Microcline	Ilmenite
Hornblende	Leucoxene
Actinolite	Titanite
Diopside	Monazite
Augite	Xenotime
Enstatite	Hematite
Hypersthene	Limonite
Muscovite	Kaolinite
Sericite	Chlorite
Tourmaline	Serpentine
Zircon	Epidote
Apatite	Calcite
Rutile	Dolomite
Biotite	Pyrite

Quartz.—Quartz is by far the most abundant mineral in all sands examined. It usually constitutes over 90 per cent of the make-up of the old sandstones. Only twelve out of ninety-one samples examined contained less than 90 per

cent of quartz. The most impure sandstone inspected had about 75 per cent. The purest sand on analysis showed a little more than 98 per cent of quartz.

Quartz is also the principal mineral in sands selected for molding purposes but in some cases it is slightly less than the sum of all the accessory minerals. In glacial drift sands it usually ranges from 50 to 70 per cent. It may constitute as much as 90 per cent of residual sands derived from weathering of the sandstones.

Feldspars.—Feldspars probably rank next to quartz in abundance and distribution. About three-fourths of the sandstone samples have feldspar. Plagioclase was recognized in one-fourth of the rock samples and orthoclase in one-fifth. Both are almost invariably much decomposed and in many cases can only be called "much-altered feldspar" without closer identification. Microcline is present in more than one-half of the samples and is one of the principal accessory minerals. It shows little decomposition even in the oldest sandstones. In the most arkosic sandstones of Ohio the feldspar content is usually less than 10 per cent.

The glacial drift sands have a large percentage of feldspar. This may be as much as 25 per cent in some cases. Orthoclase and plagioclase showing little or no decomposition are common. These minerals are entirely wanting in the residual sands but microcline is occasionally found.

Amphibole.—Hornblende and actinolite, the common varieties of amphibole, are almost entirely limited to the recent sands. Nearly every glacial drift sand contains actinolite and a lesser amount of hornblende. A few of the sandstones have much decomposed remnants of what appears to be actinolite. That these minerals were formerly present in many of the sandstones is shown by chlorite and other alteration products.

Pyroxene.—The common varieties of pyroxene in sands are diopside, enstatite, and hypersthene. Augite is less common. All are limited to recent sands of glacial drift origin. No pyroxene was seen in the sandstones but its former presence is indicated by alteration products.

Mica.—Muscovite flakes visible without a microscope are present in about two-thirds of the sandstone samples and one-half of the uncemented sands. Sericite is a common product from the alteration of feldspars. Biotite is rare even in the glacial drift sands.

Tourmaline.—This is very widely distributed. It was found in nearly three-fourths of the samples examined.

Zircon.—Zircon is nearly always present. It was found in over four-fifths of the samples.

Apatite.—About one-half of the samples were found to contain apatite. Both inclusions and free grains are common.

Rutile.—Nearly every sand has a small amount of rutile. Microscopic hairlike inclusions in quartz and free grains are the modes of occurrence.

Garnet.—Garnet is one of the principal accessory minerals of glacial drift sands. It was not found in any of the sandstones or residual sands.

Corundum.—Corundum is occasionally found in sands of all ages.

Magnetite.—More or less magnetite is always present. It is found both as free grains and inclusions in other minerals. In the glacial drift sands it is a prominent constituent.

Ilmenite and leucoxene.—Ilmenite is sometimes mixed with magnetite. Its presence is shown by leucoxene, an alteration product.

Titanite.—Titanite is occasionally seen in the recent sands of glacial drift origin.

Monazite.—Monazite is sparingly distributed in very small amounts in Ohio sands. It was noticed in three recent sands and seven sandstones.

Xenotime.—Xenotime is occasionally found in small amounts in sandstones near the base of the Coal Measures and in residual sands derived from these. It was noticed in twenty-two rock samples most of which were taken from the Sharon Conglomerate.

Hematite.—Hematite is quite common as inclusions in quartz. Earthy red hematite is sometimes a cementing material in sandstones.

Limonite.—Limonite is always present. It is a common cementing material in sandstones. In most of the sandstones examined the limonite content is less than 2 per cent. The grains of residual sands are usually thickly coated with limonite.

Kaolinite.—Kaolinite is a prominent constituent of most sands. In feldspathic sandstones it may constitute several per cent of the make-up.

Chlorite, serpentine, epidote.—These are of common occurrence in the Carboniferous sandstones. They are largely responsible for the greenish and bluish colors so often seen in those rocks.

Calcite and dolomite.—These were found as cementing material in the Sylvania sandstone of northwestern Ohio. Slight amounts, probably comminuted limestone, are sometimes seen in the glacial drift sands.

Pyrite.—No pyrite was seen in the sand samples but small limonite stained cavities probably due to oxidation of pyrite were seen in one sandstone. It is common in the deeper workings of quarries.

One of the interesting features brought out by the investigation is the entire absence of garnet in the old sandstones of Ohio. Inquiry and personal search show that this is not a local condition but that the scarcity or absence of garnet in the older sandstones is prevalent in widely separated regions. The West Virginia Geological Survey has recently made a petrographic examination of about thirty sandstones and garnet was found in only one of these—a sample from the Dunkard series.[1] Dr. A. A. Julien, whose study of sands has been very extensive, writes: "The

[1] G. P. Grimsley, "Iron Ores, Salt and Sandstone" *West Virginia Geol. Surv.*, IV (1909), 447.

scarcity or absence of garnet in the older sandstones generally prevails, I think, in all regions. I first recognized this in the Carbonic sandstones of Great Britain and soon afterward in those of Arabia Petræa and of northern Africa. It is also markedly absent or rare in the St. Peter, Cambrian, and older quartzites of this country."

In order to obtain data as to the occurrence of garnet in the older sandstones of eastern North America, a number of rock samples were examined. These were taken from collections of the Geological Department of Columbia University, and represent most of the important sandstones of the Paleozoic of the Appalachian region. There follows a summary of the results:

Cambrian: (1) Etcheminian conglomerate, Hanford Brook, Nova Scotia. Zircon present. No garnet seen. (2) Feldspathic quartzite, contact with pre-Cambrian. Doe River, Tenn. Zircon, tourmaline, and microcline seen. No garnet. (3) Sandstone, Iron Mountain, Mo. Plagioclase and zircon found, also a few grains of garnet.

Ordovician: St. Peter sandstone, Iowa. No garnet.

Silurian: Sylvania sandstone, southern Michigan and northwestern Ohio. No garnet.

Devonian: (1) Oriskany sandstone, Huntington, Pa. Zircon, tourmaline, and plagioclase (little decomposed). No garnet. (2) Oriskany sandstone, Vienna, Ontario County, N.Y. Zircon and calcite. No garnet. (3) Catskill sandstone, Monkey Hill, Delaware County, N.Y. Zircon and tourmaline. No garnet. (4) Catskill sandstone, Mill Creek, Pa. Tourmaline and zircon. No garnet. (5) Catskill sandstone, Catskill Mountains. A large number of thin sections were examined. Quartzite pebbles were seen, showing that the formation was derived in part from the reworking of a previous sandstone. Considerable well-preserved feldspar, and much epidote and chlorite are present. No garnet was seen.

Carboniferous: (1) Pocono sandstone, Dungannon, Pa. Zircon, tourmaline, and titanite present. One grain of garnet was seen. It had a pitted surface as though affected by solution. (2) Pocono, Pottsville, Pa. Zircon and tourmaline. No garnet. (3) Mauch Chunk sandstone, Cave Gorge, Dungannon, Pa. Zircon, plagioclase, tourmaline. No garnet.

As was mentioned in a previous page, garnet was found in one sample from the Permian of West Virginia. The Triassic beds of New Jersey and Connecticut abound in garnet. The grains are always fresh appearing with little sign of solution or alteration.

In attempting to account for the scarcity or absence of garnet

in the older sandstones, these questions arise: Is it due to the inability of garnet to withstand solution and decomposition incident to weathering? Is garnet sufficiently resistant to the wear of travel to find a place in sands laid down at a distance from the source of supply? Or is the scarcity due to the derivation of the components of the sandstone from a region where garnet was not an important rock-forming mineral?

There is ample evidence that garnet is quite resistant to ordinary weathering processes. It is a common constituent of residuary sands derived from decomposed schists. The Newark series of New Jersey and Connecticut, consisting largely of coarse sandstone which would favor free circulation of ground waters, has been exposed to weathering processes for many ages; nevertheless it contains abundant garnet grains which show little evidence of solution or alteration. Furthermore the discovery of occasional particles in a few of the older Paleozoic sandstones is still stronger proof of the resistant properties of garnet. The scarcity cannot be due to mere decay since often other minerals survive which are equally or more susceptible to decay, such as feldspars and mica.

The physical properties of garnet are such that it should withstand the wear of long travel. Lack of cleavage, and hardness are in its favor. Zircon, tourmaline, feldspars, and other minerals which are somewhat similar in their physical properties to garnet are widely distributed even in the very old sandstones.

This leads to the conclusion that the materials of the older sandstones were derived from sources where garnet was not abundant. Repeated reworking of successive sandstones has doubtless furnished much of the material. Very pure quartz sands of the Sylvania type are probably entirely derived in that way. However, most of the great sandstone formations have constituents which have certainly come rather directly from crystalline areas. This is especially true of the Catskill series and the "Coal Measures" sandstones.

Garnet is a characteristic mineral of regional and contact metamorphism. It is common in gneisses and schists of sedimentary origin. As an original mineral in igneous rocks it is much less common. The gneisses and schists of the Appalachian region are

abundantly provided with garnet. Glacial drift drawn from such sources has so much of the mineral that it is second only to quartz in abundance. The Triassic beds of the east, fairly reeking with garnet, furnish an illustration of a sandstone built largely from materials derived rather directly from the crystallines. Conditions of sedimentation during "Coal Measures," Mauch Chunk, and Catskill time were probably not greatly different from those that prevailed during the formation of the Triassic beds. All are either continental or near shore in origin.

To the writer it seems that the difference in mineral content between the Triassic and the older sandstones indicates a quite different source of material. While it is obvious that gneisses and schists contributed very extensively to the Triassic beds, it seems probable that such rocks did not furnish much of the materials of the older sandstones. A large portion of these have doubtless come from crystalline sources, but the minerals indicate that the rock may have been igneous rather than metamorphic. It is conceivable that a peridotite or gabbro furnished the ferromagnesian minerals so abundant in the Catskill series, while a granite was the source of the zircon, tourmaline, and muscovite of the "Coal Measures" sandstones.

It is becoming more and more evident to geologists that the mountain-making processes which took place at the close of the Paleozoic were accompanied by the intrusion of extensive igneous masses and the metamorphism of the country rock into schists. The work of Loughlin[1] and others has demonstrated the magnitude of these changes in Rhode Island. A number of intrusive masses, mostly granite, in the highland region of New York and New Jersey, are known to be post-Ordovician and may be of the same age as those in Rhode Island. Recently a report has come from Virginia of the finding of fossils in schistose slates of the Piedmont belt. These slates were formerly regarded as pre-Cambrian but the fossils show them to be Upper Ordovician in age.[2] Thus it is

[1] G. F. Loughlin, "Intrusive Granites and Associated Metamorphic Sediments in Southwestern Rhode Island," *Am. Jour. Sci.*, XXIX (1910), 447–57.

[2] Thomas L. Watson and S. L. Powell, "Fossil Evidence of the Age of the Virginia Piedmont Slates," *Am. Jour. Sci.*, XXXI (1911), 33–44.

seen that as more detailed work is done in the region of the crystalline rocks, more and more of the "Complex" is differentiated and removed from the pre-Cambrian and proved to be more recent.

Is it not possible that the general scarcity of garnet in the older sandstones may be due to the more recent formation of many garnetiferous schists which are now classed as pre-Cambrian?

SOME OBSERVATIONS AND EXPERIMENTS ON JOINT PLANES

PEARL SHELDON

II

EXPERIMENTAL WORK

Systems of cracks at right angles to each other were obtained by Daubrée[1] by twisting plates of ice and glass and by compressing mixtures of beeswax and resin. W. O. Crosby[2] found that if plates twisted not quite to the breaking-point were given a shock they would break in cracks at right angles to each other. Systems of cracks due to torsion have been studied experimentally by G. F. Becker.[3] For this reason and because the conditions involved in the torsion experiments do not agree closely with the conditions under which the joint planes of this region were formed, these experiments were not repeated.

Theoretically and practically work similar to Daubrée's pressure experiments seemed most likely to give satisfactory results. Daubrée applied pressure over the square ends of blocks of wax. The sides were left unconfined so that deformation could take place on all sides. Besides large planes of slipping, the deformed blocks showed a network of fine even cracks at right angles to each other and parallel to the larger breaks. Daubrée compared the larger breaks with faults and the smaller with joints. Unfortunately, the outcrops of the cracks, though at right angles to each other, made angles of 45° with the direction of pressure, and, judging from his figures, the planes of breaking were parallel to the faces of an octahedron. This does not agree well with the commonly observed angles between joint faces, and the usual strike and dip relation of joints indicates that they are nearly at right angles to, and parallel to, the pressures acting at the time they were formed.

[1] *Études synthétiques de géologie expérimentale*, 300–52.

[2] *Am. Geol.*, XII (1893), 368–75.

[3] *Trans. Am. Inst. Mining Engineers*, XXIV (1894), 130–38.

Instead of beeswax and resin, mixtures of paraffin and resin were used in the experiments. Several precautions were necessary in order to obtain good results. Paraffin alone faulted with a slickensided surface along a plane making an angle of 45° with the pressure, but no fine cracks appeared. The addition of a little resin, however, brought the desired cracks. The amount of resin used varied from just enough to stain the paraffin yellow to enough to give it a brown color. No good results were obtained with the material above a freezing temperature and the best results were had at about 0° F., or, rather, at the lowest temperatures available. Artificial cooling did not give such good effects as those obtained by allowing the material to harden by exposure to the air on the coldest winter days and subjecting it to pressure at the same temperature. The paraffin was cooled in tins and cut into convenient sizes while soft. It was found that the cracks came out better on the natural upper surface than on the smoother, glazed sides and bottom which had been in contact with the tin and better than on surfaces which had been planed smooth. This made it necessary to cool the paraffin carefully; otherwise, with its large contraction, the surface became badly wrinkled. It was also found best to cool the material rapidly and use it as soon as hard. The better results seemed to be connected with lack of uniformity in the material. Results were better on the less regular surfaces and on material so recently cooled that it probably was not equally hard throughout. Likewise, since it was cooled by being placed on snow with the upper surface exposed to the air, the rates of cooling of the upper and lower surfaces were different, with a consequent variation in grain through the mass. Daubrée was careful to have his blocks regular in shape, with faces planed smooth, and probably his material was nearly homogeneous. The experiments on paraffin showed that such care was more than wasted in preliminary experiments like these, where no attempt was made to use carefully regulated conditions for the purpose of obtaining mathematical results.

In size the blocks used were from two or three to eight or ten centimeters in length and breadth and from less than a centimeter to three centimeters in depth. These dimensions were employed in all combinations of long and narrow to square, thick, or thin.

The blocks were compressed in a small hand vise and one or two of the dimensions of the blocks were often greater than the corresponding dimensions of the jaws of the vise. Little attempt was made to smooth the paraffin to regular shape; therefore the application of the pressure was often very uneven. The varying conditions made it possible to trace cause and effect, and, since several scores of blocks were compressed and each showed different effects in its

FIG. 9.—Photograph of a block of paraffin after compression. ×1.4

different parts, the results may be taken as general for the given material and given conditions.

Figs. 9 and 10 are photographs of two of the blocks after they were compressed. The pressure was applied parallel to the plane of the paper in a line up and down the page. These blocks were hardly of average value for study but they were stained so dark with resin that it was possible to photograph the white cracks. Attempts to photograph the lighter-colored specimens by transmitted light were only partly successful. Fig. 11 is a composite showing the more common results of compression. The pressure was applied over the face *abcd* and the opposite face. Near the right edge is shown the result of a fairly even pressure over a rough face. With even pressure and a smooth face the material would

break and slip with a slickensided surface along a plane making an angle of 45° with the pressure, that is, a plane whose outcrop on the face *abef* made an angle of 45° with the edges and whose outcrop on *bdfg* was a straight line parallel to the right edge. On account of the uneven face some points usually received a greater thrust than others so that the material broke in sections, the outcrops on the flat faces being parts of ellipses as shown in the figure. These sections each moved along a slipping plane of about 45° with the pressure, so that where there were several rows of semi-ellipses

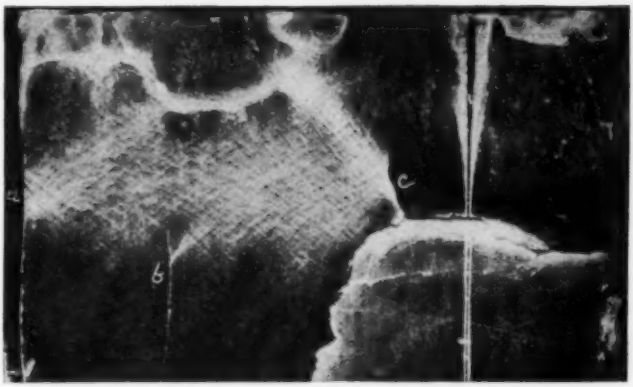

FIG. 10.—Photograph of a block of paraffin after compression. ×1.4

the material had been broken along several parallel slipping planes. The outcrop of the main slipping plane is shown from *h* to *i*. There was a similar tendency for the planes of slipping to break off the corners along the edges of the end faces. This is shown at *h* and *i* where the breaking plane extends farther in than it does near the center of the long edges. Sometimes this was carried so far that the point *h* was near the center of the shorter edges.

At the left edge is shown the result of a thrust which was stronger along the center of the face than near the edges *ac* and *bd*. In practice this occurred when the face of the material was wider than the jaws of the vise. The effect was usually to split the material in a nearly horizontal plane which, farther in, merged into a small slipping plane at 45° with the pressure with an outcrop along *jk*.

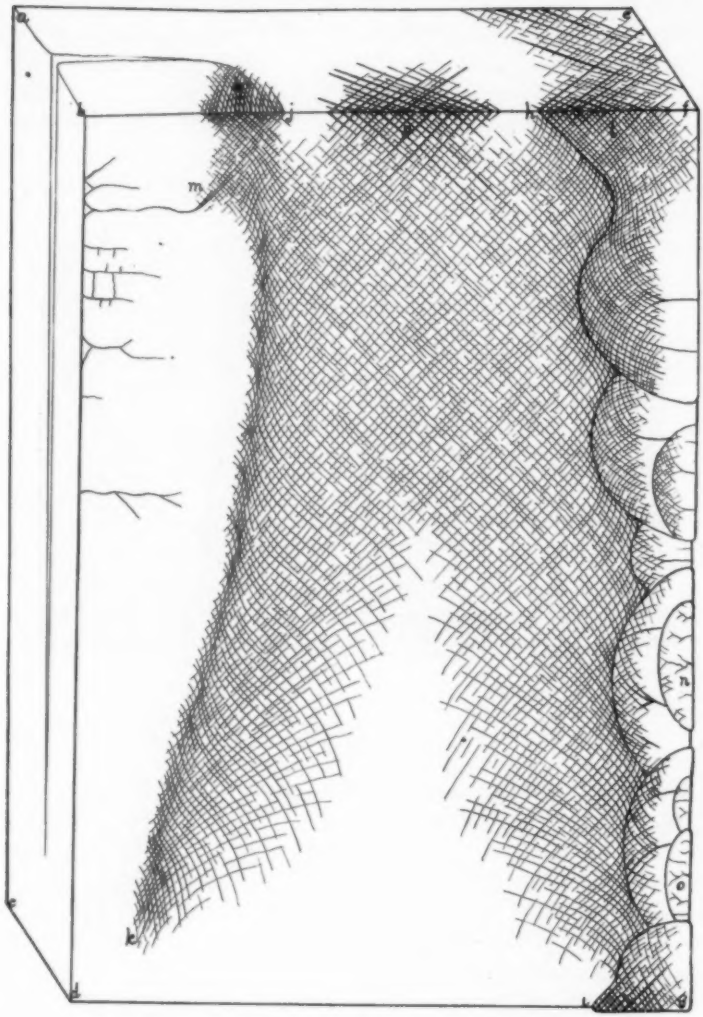

FIG. 11.—Composite showing the cracks produced by compression

Along *hi* slipping has taken place but *jk* represents the condition just before breaking at the surface. The outcrops of the slipping planes occurred on either the face *bfgd* or *aec* or both, depending upon the application of the pressure.

With the distance between the jaws of the vise small compared with the length and especially with hard material at the lowest temperatures, the blocks often broke in planes nearly parallel to the end faces *abef* and *cdg*. The break through the middle was nearly a plane face and the breaks toward the ends were convex outward, resembling a pile of thin cards compressed at the ends so that the cards bow out. In these breaks the faces separated instead of slipping on each other and slickensiding. With material cooled rapidly to a low temperature these faces were usually covered with even, featherlike markings which were of interest because they closely resembled the patterns which J. B. Woodworth[1] found on the faces of joint planes. The patterns consisted of a central smooth axis from which extended scales of the paraffin shaped like a half-crescent with the point toward the axis. The scales were free along the concave margin and passed into the material along the convex edge. The position of the axis of the feather depended on the application of the pressure and the homogeneity of the material but was usually near the middle of the breaking plane.

With similar hard material and the pressure applied to points as along *fg* the breaking took place along surfaces shaped much like half a bell with the rim in the face *bfdg*. These bell-shaped surfaces were also covered with half-crescent scales with their points toward the place where the thrust was applied and their broader portions radiating outward.

Such markings are associated with separation of faces rather than slickensiding. Further study of them might be of interest in connection with the question of whether joint faces are separated at some time in their formation or are always held tightly together. Such markings were not seen on the joint faces of the Ithaca region.

NETWORK OF CRACKS

Besides the large breaks, there was a system of intersecting even cracks similar to the fine network found by Daubrée. He compared

[1] *Proc. Boston Soc. Nat. Hist.*, XXVII (1896), 163–83.

them with joints. Their behavior under various conditions of pressure and breaking of the material is shown in Fig. 11 and the photographs.

Perhaps the most conspicuous result of the experiments on paraffin concerned the relation between these cracks and the forces at right angles to the active pressure. Whatever the direction of the cracks in the inner part of the block, whenever they approached the unconfined edges they turned so that their outcrops made angles of 45° with the edges. This is shown at *j*, *l*, and *i* in Fig. 11 and at *a* in Fig. 10. At *a* in Fig. 9 the same thing was present but the change occurred abruptly so near the edge that it did not show in the photograph. The cracks also turned or strengthened when they approached larger breaks as shown at *m* in Fig. 11, at *b* and *c* in Fig. 10, and from *b* to *c* in Fig. 9. Wherever these fine cracks approached free edges they immediately turned to the 45° position. In practically all cases the cracks became stronger near such edges as is shown in the photographs and indicated in the drawing.

Obviously, in rocks there would be few such places where the material acted on ended abruptly. In practically all cases deformation would be resisted by strong molecular forces at the sides and usually by the influence of overlying beds. Hence the cracks obtained by Daubrée and those at the edges and surfaces of the paraffin blocks could not be expected closely to imitate joints. More satisfactory results would be expected near the center of the block where the molecular forces would have a normal effect.

Near the edges there were often irregular cracks making small angles with the pressure like those shown at the left edge of Fig. 11. On the smaller semi-elliptic surfaces they were often forked, as at *n* and *o*, so that the portions of the break made equal angles with the line of pressure. Usually at some distance from the edge and beyond these irregular breaks the network of cracks appeared. They usually started at a fairly even distance from the edge, though often a few extended backward to the edge. At first they made oblique angles with each other, the line of pressure bisecting the acute angle. Soon they spread to right angles and then to larger angles near the outcrop of the slipping plane *hi*. There the line of pressure cut the obtuse angle. The cracks sometimes

became nearly perpendicular to the line of pressure and appeared as a mass of wavy lines as at *ab* in Fig. 9.

Where the application of the pressure split off part of the block as along the left edge of Fig. 11 the cracks usually started farther from the edge and omitted the acute-angled portion as along *jk* in Fig. 11 and *ab* in Fig. 9. Thus near the outcrop of the slipping planes these cracks were nearly parallel to the outcrop and were arranged symmetrically about the line of pressure.

The preceding are the forms of cracks which were most common but in the better specimens the central part of the block was usually covered with cracks and these were more regular than in the rupture portions of the paraffin. They occurred evenly over the large faces, commonly making angles of 90° with each other and 45° with the pressure. At their connection with the oblique-angled cracks near the slipping planes the angles changed rapidly. These cracks were usually stronger near the center of the end edges, as at *p* in Fig. 11, than at each side of the center. In the block shown in Fig. 10 the breaking lines corresponding with *jk* in Fig. 11 both occurred near the center so that the cracks across the center showed a compromise between the large angles near the breaking lines and the right angles of the unbroken center of a block.

In Fig. 11 is shown the effect of a greater thrust near one end of the block. This was commonly caused by a greater width of the block at one end. Where the thrust died out the cracks were not symmetrical about the general line of pressure. This is shown in the lower central part of Fig. 11. Sometimes locally, as near an irregular breaking edge, a few cracks would occur in nearly the shape of a fan, one set forming a few rays and the other set curving at right angles to the rays.

Since the diagonal cracks made angles of 45° with the edges of the end faces, the planes of the cracks near the ends were nearly parallel to the faces of an octahedron. The inclination of the cracks near the center of the block could not be determined, but in some cases where the oblique cracks continued to a point near the edge the outcrop on the end faces was less than 45° with the vertical, as shown at *q* in Fig. 11. Probably the inclination varied

as much from 45° as the direction did in the parts of the block away from the influence of the ends.

Fig. 11 shows the general appearance of the cracks with the exception that the lines were seldom sharp except near the edges. They were usually blurred by the crushing of the material, as shown in the photographs.

FIG. 12

Closer examination of some of the diagonal cracks on the upper faces showed that the lines were not continuous but consisted of a series of more or less sigmoid lines arranged in diagonal rows, as shown on an enlarged scale in Fig. 12. Sometimes the diagonals consisted of a series of steplike fine cracks, as shown in the lower left-hand corner. Evidently where the thrust was sufficient to cause rupture the breaking took place along the diagonals, but a lesser thrust left the series of smaller cracks which had been formed first. These cracks were usually a millimeter or two in length.

FINEST CRACKS

When the material was examined by transmitted light with a hand lens it was found that still other cracks were present. Over the upper surface were many lines like those shown enlarged in Fig. 13. They looked like rift in granite.[1] They were about a millimeter long and were fine and sharp. They occurred especially where the thrust was unusually strong, in front of the semi-elliptical breaks, though they were often present between the slipping plane and the face where the pressure was applied. They often

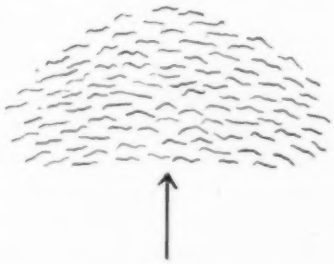

FIG. 13

[1] R. S. Tarr, *Am. Jour. Sci.*, 3d ser., XLI (1891), 267–72.

occurred in the same places as the larger diagonal cracks, so that the surface showed two sets of opaque 45° cracks with these fine, wavy lines superposed upon them over the whole surface and arranged nearly at right angles to the pressure. Where the thrust decreased laterally there was a suggestion of a change in direction which would make the average direction of the cracks slightly concave toward the thrust.

When the paraffin was pared down so that a section from the interior could be studied by transmitted light it was found that in sections several millimeters thick there were opaque diagonal lines, but these lines no longer made angles of 90° with each other and 45° with the pressure as at the surface. The angles between the two were usually about 70°, with the line of pressure bisecting the acute angle. These were commonest where the thrust was unusually strong.

When the paraffin was cut to a thickness of about a millimeter these opaque lines disappeared and the material was seen to be full of fine, sharp, wavy cracks about a millimeter long like those shown in Fig. 13 but parallel to the pressure. Examination with a hand lens did not show that they were arranged in diagonal rows, but, since it was found uniformly that a thicker section gave broad opaque lines and these lines disappeared entirely in a thin section and fine wavy lines appeared in their place, it seemed, from analogy with the sigmoid lines and diagonals of the upper surface, that the breaking within the mass of paraffin consisted of fine cracks nearly parallel to the pressure, the cracks arranged in diagonal series so that by superposition they gave opaque lines in a thick section.

Thus in passing from the unnatural surface conditions to the interior of the mass where conditions would be more similar to those in the rocks the angles between the larger lines decreased so that the lines made a smaller angle with the pressure and the smaller cracks of which each line was made became straighter and entirely separated from each other. Here was a set of cracks uniformly present within the mass subjected to pressure, the cracks each nearly parallel to the line of pressure and suggesting an arrangement in two sets with the pressure bisecting the acute angle.

Unfortunately the fine lines at right angles to the pressure

which were seen abundantly on the surface were not found within the mass, though certain fine lines may have been their representatives. If so, they were smaller than at the surface and too fine compared with the grain of the material itself to be studied with any accuracy. All of these finer cracks, both at right angles to, and parallel to, the pressure, could be studied only in thin sections by transmitted light and required a lens, but they were practically the same throughout the large number of specimens in which they were found, so that their general character was evident. The cracks were too fine for a determination of their inclination, but it probably was not large, since the cracks appeared as sharp lines instead of broad, opaque lines as would be the case if they ran diagonally through the material. Both of the sets of finer cracks appeared in the central unruptured portions of the paraffin as well as in the broken parts. The material appeared unbroken but when it was held before a light the places of greater thrust were found to be opaque, and examination with a lens showed the fine lines which caused the opaque appearance.

The experiments were carried about as far as possible under these conditions, since the most interesting cracks were too fine for study with the naked eye and the irregularities of the material were large compared with the size of the cracks. Further study should be made with finer-grained material which could be studied with a microscope, or the conditions should be such as to give larger cracks.

DEDUCTIONS

AGE OF THE JOINT PLANES

STRIKE JOINTS

It is apparent that the strike joints were formed in connection with the low folds of this region. Their average strike corresponds too closely with the axes of the folds to be accidental. If they had been formed before the folding with a uniform, nearly vertical inclination they would now be nearly at right angles to the bedding planes; that is, if the planes of the joints were produced they would meet below the axes of anticlines and above the axes of

synclines. The reverse was found to be true. If they originally made a uniform moderate or large angle with the vertical, folding would have increased the angle on one limb of the fold and decreased the angle or reversed it on the other. Thus angles such as were actually found might be produced on one limb of the fold but not on the other. If the joints had a varying hade which reversed near the axes of subsequent folds the present angles might be produced, but that is too improbable.

The joints might have been formed with uniform, nearly vertical inclination after the beginning of the folding. Subsequent subsidence of the folds would give the angles observed. This is not probable, because the faulting indicates that much of the movement took place after the formation of the joints. This theory would require a reversal of all the later folding and enough more to reverse the joints. It would not alter the question of the age of the joints, since, if their hades were produced in this way, they must have been formed during the folding.

The upper limit for the date of the jointing is set by the faulting. The nearly horizontal faults of this region uniformly displace the joints which they cross; therefore the joints were formed before the faulting, or at least before the end of the movement along the fault planes. These faults were presumably formed in the time of active folding here, that is, during the Appalachian Revolution. This sets the date of the joints as somewhere between the beginning of the pressure which caused the folds and the climax of the folding as indicated by the active faulting. Unless the joints were formed by subsidence of the folds their direction of inclination is, in most cases, the same now as when they were formed. The angles, however, have been altered by later folding and in some cases may have been reversed. This may explain some cases where the reversal of direction takes place at one side of the axis of a fold.

DIP JOINTS

The evidence for the dip joints is not so conclusive, since the lack of detailed knowledge of the pitch of the folds prevents a comparison of the variation of the hade of the joints with the variation of the folds. From what is known of the pitch the hade of

the dip joints seems to be mainly in the same direction as the pitch. At any rate, their hade is not such as would be produced by subsequent uplift of joints formed with uniform, nearly vertical inclination.

As in the case of the strike joints, the upper limit is set by the faulting. They cannot be older than upper Devonian, the age of the rocks in which they occur. One set of dip joints is nearly at right angles to the axes of the folds and the other set lies near the local resultant force acting during the folding as indicated by the strike of the faults. The angle between the two dip sets varies with the intensity and pitch of the folds. They are not so well differentiated near the weak Watkins anticline as near the strong and pitching Shurger Point fold and the strong Alpine anticline south of the Enfield syncline. The comparative strength of the two sets varies also. The experimental work showed that a variation in the forces at right angles to the active pressure had a large effect upon the cracks. The pitching of the folds and the large angle shown by the faults between the local resultant force and the general force at right angles to the axes of the folds indicate that the forces at right angles to the pressure varied considerably from place to place during the folding. Under such conditions the two dip sets would be expected to differ in strength and to vary with the folds if they were formed at that time.

The experiments showed that subjecting paraffin and resin to pressure gave fine cracks at right angles to the pressure and nearly parallel to the pressure. The latter were developed from a double set bisected by the line of pressure and might themselves form a double set if they could be measured carefully. During the Appalachian Revolution such a horizontal pressure was applied to the strata and should have formed cracks having directions like the observed joint planes. It has not been shown that there was enough disturbance of this region between the time of deposit of the rocks and the formation of the folds to have produced joints. If that were the case two independent groups of strike and dip joints should be found, for experimentally both strike and dip cracks were formed by a single application of pressure. There are two sets of dip joints found but they seem to be too closely

connected to have been formed by entirely separate forces and the strike joints distinctly belong to a single set.

It has sometimes been assumed that joints at right angles to each other were formed at separate times, the forces producing the second set being at right angles to the forces producing the first set, that is, both sets bore the same relation to the forces which caused them but the forces were in different directions the two times. Opposed to this is the fact that the strike and dip joints are not similar. If a certain set of forces produced the strike joints, then a similar set of forces acting at right angles to the former forces should give another set much like the strike joints except in direction. This is not the case in the Ithaca region. Experimentally cracks were produced in all the required directions during the same application of pressure and it does not seem necessary to assume that strike and dip joints were formed by separate applications of pressure in the rocks.

In most cases the master joints are sharply cut by the faults but in some cases there is evidence that some strain existed along the fault planes at the time the joints were produced. Near the right in Fig. 1 is a dip joint which is strong and normal excepting near the fault line where it abruptly breaks into a fanlike set of radial small cracks with the point below. This fan is about a foot across and the fault crosses its center. Above the fan the joint becomes normal again. Evidently when the joint was formed there was some strain at the place where movement occurred later or perhaps the faulting had already begun. Many of these fanlike irregular joints were seen near faults and were evidently due to strain at the fault planes, but the others were not examined for their relation to the master joints. Investigation would probably show that more of these are connected with the master joints and in the case described the fan is certainly a part of an otherwise normal joint belonging to one of the dip sets.

The evidence thus indicates that all the master joints were formed in the earlier part of the period of folding. Probably when the pressure reached a certain value, less than its maximum, the joints were formed rather abruptly. Further pressure caused faulting, or perhaps some faulting occurred before the formation

of joints and the continued pressure caused further slipping which displaced the joints. It is not necessary to assume that the strike and dip joints were formed at exactly the same time. They are unlike in other respects and may have been in this. In the experiments the fine cracks could not be watched as they were formed so that their time relation was not determined.

EVIDENCE OF THE DIKES

All the known dikes of this region are in the dip joints. None are found in the strike set. Kindle[1] has suggested that the dip joints were older than the Appalachian uplift and the igneous matter was intruded before the formation of the strike set. Another suggestion that has been made assumes that the faces of the strike joints were held tightly together by pressure so that the dike material could not force its way in. Opposed to this is the fact that many of the dike streamers are exceedingly thin, penetrating fine breaks.

The dikes are mostly in the Portage rocks and in these the dip joints are usually the stronger. Judging from the experiments the faces of strike joints would be held together but under some conditions there might be a tendency for the faces of the dip joints to separate. This would allow the igneous matter to enter the dip joints more easily. Perhaps the dip joints antedate the strike set, even though both were formed during the folding. Since the dikes are faulted, they were obviously formed between the time of the dip joints and the climax of the faulting. Further study of the relations between dikes, joints, and faults would probably be useful in determining the exact order of formation of the various sets of joints, but from the present evidence it does not seem necessary to assume that the dip sets were present before the Appalachian Revolution in order to explain the dikes.

The time of formation of the minor joints is not so evident. Probably most of them were formed at about the same time as the master joints. Along the walls of the dikes the rocks are cut by innumerable small jointlike cracks which were evidently formed as a result of the pressure of the dike material.

[1] *Folio 169*, p. 13; field edition, pp. 96–97.

The Ithaca region seems particularly favorable for the study of joint planes. The stratigraphy is comparatively simple, showing only one time of crustal movements sufficiently great to be accompanied by jointing. The pressure was strong enough to produce joints and folds and faults with which the joints could be compared, but it did not carry the folding far enough entirely to reverse the joints and so complicate the record. In regions of higher folds the hades of the joints should be studied with the plane of bedding rather than the horizontal as a datum plane.

CAUSE OF THE JOINT PLANES

Geologists are not agreed upon the cause of joint planes in stratified rocks. On account of the observed relation between joints and the strike and dip of rocks it is usually conceded that they are connected with movements of the earth's crust. Some of the theories of the cause of joints have been abandoned. Among those still recognized are tension, earthquake shock, torsion, and shear.

TENSION THEORY

According to the tension hypothesis joints are formed during folding. As the folds develop there is tension along the upper surface of anticlines and the under side of synclines. The rocks then crack in planes whose outcrops are parallel to the axes of the folds. At right angles to the axes the pitch of the folds causes another set, the dip joints. A general objection to this theory is the character of the joint faces. They are smooth and are remarkable for passing directly through hard masses like pebbles or concretions, instead of around them. The Hamilton shales of this region show this very well. The rock is mostly an even shale but there are several bands of hard concretions. Some of the joints do not pass through the concretions but probably the majority cut them in a smooth plane even with the rest of the joint face. It does not seem probable that a crack due to tension and separation of faces would pass so smoothly through concretions instead of around them. The general smoothness of a joint face in shale is very unlike the surface caused by breaking rock apart.

Joints formed by tension would be arranged radially about

the folds, that is, if their planes were produced they would meet below the axes of anticlines and above the axes of synclines. The reverse was found to be true. It seems difficult to explain the hade of the strike joints by the tension theory. Neither does this theory account for the double nature of the dip joints nor for the mass of minor joints in all directions. The perfection of jointing in some parts of this region is out of proportion to the amount of cracking necessary to relieve the tension in such low folds.

EARTHQUAKE THEORY

W. O. Crosby[1] offered an earthquake hypothesis as an explanation of joints. Later[2] he emphasized the effect of shock on rocks already under strain rather than shock alone. Crosby stated some of the more important objections to the formation of joints by earthquake shock alone. Such breaks would not become approximately vertical for some distance from the epicentrum and then the energy of the shock would be largely dissipated. In the Ithaca region the inclination of the master joints is nearly vertical and in changing from one side to the other passes through the vertical, not through the horizontal as would be expected from earthquake waves. In order to explain the commonly observed right-angled relation of joints, it has been assumed that after one shock had produced a set in one direction a large component of a subsequent shock would be relieved by slipping along the already existing planes, unless it was at right angles to the earlier shock, except in case of very rapid vibrations. Only one set of planes would be formed by each shock. The direction of the strike joints might be accounted for by making the focus of the earthquake a long fault parallel to the axis of the fold. An objection to the earthquake hypothesis apparent in this region is the symmetry between the joints and folds. It is not probable that the folds would influence cracks due to earthquakes to such an extent nor is it probable that separate shocks occurred simultaneously in the different folds to cause a reversal of the joints near each axis.

The earthquake theory alone seems awkward, since it requires

[1] *Proc. Boston Soc. Nat. Hist.*, XXII (1882), 72–85; XXIII, 243–48.

[2] *Am. Geol.*, XII (1893), 368–75.

an improbable system of separate shocks to account for the several sets of major joints and the mass of minor joints. These shocks must have been symmetrical with the forces producing folding, and the resulting breaks were of different character at different times. It seems simpler to refer the joints mainly to the orogenic forces, but perhaps as in Crosby's combination of shock and torsion the shock attending crustal movements materially affects the formation of cracks in strained rocks.

TORSION THEORY

In Daubrée's torsion experiments the material broke in two sets of cracks, making angles of 90° with each other and 45° with the axis of torsion on the large faces of the plates. The inclination as shown on the narrow side faces was as high as 50° with the vertical, though usually less. Becker repeated these experiments with plates of glass of various dimensions. He obtained the same directions of outcrop on the large faces as were found by Daubrée and he also found that the breaking surfaces were curved. Sometimes the outcrop on one of the large parallel faces of the glass was straight and on the other S-shaped.

Many of the minor joints of the Ithaca region are shaped like the surfaces Becker obtained by torsion and they are probably due to this cause. The most important of the curving joints are those which strike north of west. The well-developed joints of large hade found near the Shurger Point fold also resemble breaks due to torsion. The innumerable small joint faces are probably due to local twisting.

The master joints do not show such curvature in a single exposure, though perhaps if their full extent were seen they would be found to have a twisted surface. The torsion theory has been criticized because the breaks make angles of 45° with the axis of torsion while joint planes are nearly parallel to the dip and strike of rocks. If the ends of a piece of cardboard are twisted in opposite directions the resulting ridge runs diagonally between the corners or nearly parallel to one of the sets of cracks obtained by Daubrée. In order to twist the plates, however, Daubrée applied a couple at right angles to the plane of the large faces. In the rocks this

would correspond with a set of vertical forces. The pressure forming the folds of this region was tangential to the beds rather than vertical; therefore the conditions in the rocks were unlike the conditions of the torsion experiments, though there was probably some variation in the vertical forces. Moreover, in comparing the various theories for the formation of joints it may be considered that torsion like that employed by Daubrée is only a special case of shear.

SHEAR THEORY

Daubrée also obtained a network of cracks by a compression which caused shearing stresses. Becker[1] has given a mathematical treatment of strains in rocks and explains joints as the result of shear. The field observations show an intimate relation between the master joints and the forces which caused the folding. Those forces are supposed to have been tangential to the beds. The symmetry of the faults in the encrinal limestone about a nearly horizontal plane is evidence that, if not vertical, the chief forces were nearly horizontal. By applying pressure to the narrow faces of blocks of paraffin fine cracks were obtained which bore nearly the same relation to the pressure which the joint planes bear to the pressure active during the folding. The pressure used in the experiments corresponded with a tangential pressure on the strata. The evidence points toward the formation of the joints as the result of a nearly horizontal pressure, but in the present state of knowledge of the relations between stress and strain in rocks the relations between joints and the strains caused by this pressure are uncertain. Strains in rocks are exceedingly complicated, since the forces vary and the materials acted upon are not homogeneous.

The joints found here do not exactly agree with the breaks discussed by Becker. They are similar in some respects but unlike in others. He concluded that faults, joints, and slaty cleavage all lie in the planes of maximum tangential strain. This implies that joints are only faults of little throw. The faults in this region were apparently formed under the same set of forces as the joint planes; yet the two are very unlike. Of three planes at right angles to each other, the faults lie approximately in one, the horizontal, and the strike and dip joints lie approximately in the other two, the

[1] *Bull. Geol. Soc. Am.*, IV (1893), 13–90; *Proc. Wash. Acad. Sci.*, VII (1905), 267–75; *Eng. and Mining Jour.*, LXXIX (1905), 1182–84.

vertical planes. Slipping may occur in two planes which have the same strike. In the encrinal limestone both these slipping planes are represented by true faults.

If there was differential movement of the joint faces during the folding, that throw was not more than a fraction of an inch. On the other hand, there was displacement of half a foot along the fault planes after the formation of the joints. If joints lie in the planes where slipping would be expected to occur, it seems strange that under forces strong enough to cause noticeable displacement along known faults there was little or no movement along the joints if the latter are incipient faults. In the actual case found in this region the joints are so nearly at right angles to the horizontal faults that the force along the fault planes had almost no component along the joint planes, hence movement along the faults could take place without slipping along the joints even though they formed planes of weakness. If pressure is applied to the rocks at an oblique angle with the joint planes after the joints are once formed, slipping would be likely to result; but such subsequent movements are not an essential part of the production of the joints.

One of the difficulties in explaining joints by pressure theories has been the presence of a set of joints apparently parallel to the pressure. The Ithaca region shows that here, at least, the dip joints really consist of two sets not parallel to the pressure but more or less symmetrically arranged about the pressure and making a small angle with it.

If the faults lie in the true slipping planes then the small hades of the joints are still unexplained. Perhaps they are due to shock associated with the strains due to the pressure. The conditions under which the joints were formed probably included translation, rotation, compression, pure shear, some torsion of the kind employed by Daubrée, and shock. To determine the exact manner of formation of joints and their relations to stresses, there is need of detailed field observations on the relations between joints and the forces producing them, as indicated by attendant faults and the axes and pitch of folds, and need of experimental work by which cracks resembling joints can be produced under such conditions that measurements may be made to determine the relations between stress and strain.

Reviews

The Geology of the Lake Superior Region. By Charles Richard Van Hise and Charles Kenneth Leith. United States Geological Survey, Monograph LII. Pp. 641; Figs. 76; Pls. 49.

All geologists interested in pre-Cambrian geology will view with pleasure the appearance of this monograph. While the work is to a considerable extent a compilation of all other important publications on this region it contains much which is new and a great deal of information, especially on the origin of the iron ores, which here appears in print for the first time. The geography, general geology, bibliography, and history of the economic development of the region are discussed in a general way. These discussions are followed by detailed descriptions of the geology of the various ore-bearing districts, the geological series, the glacial geology, the origin of the ores of iron and copper, a genetic classification of the iron ores of the world, and finally by a summary of the geological history of the region with special mention of the unconformities separating the different series.

The region covers an area of approximately 181,000 square miles of which the copper and the ten great iron-bearing districts combined make less than 3 per cent of the total. The relief varies from a maximum elevation of 2,230 feet above sea-level in Minnesota to a minimum of 376 feet below sea-level in the basin of Lake Superior.

In the section on physical geography, edited by Lawrence Martin, it is concluded from a discussion of the peneplaination of the area that the region was base-leveled in pre-Cambrian time. While the subject is treated from nearly all standpoints and the matter presented is good the reader feels that although such a statement as, "Earlier possible peneplain levels—in the Huronian for example—would have been warped or folded by pre-Algonkian deformation," appearing on p. 88, must be assigned to an oversight or a typographical error, great difficulty is experienced in distinguishing between statements which refer to the present peneplain and those which refer to the plain which was doubtless formed in the early Algonkian. Observations are made regarding the origin of the Lake Superior basin and the conclusion reached that it is largely due to graben faulting and glacial erosion.

Much new data relating to the iron ores has been collected, especially regarding their chemical composition, porosity, and moisture content, and the results have been depicted graphically on the triangular diagram which is so frequently employed in this work. It is shown that the phosphorous in the ore of the Mesabi district has come chiefly from the overlying Cretaceous rocks while in the Penokee-Gogebic district the phosphorous content of the ore increases with the percentage of iron indicating that this element was originally in the ore. In the vicinity of dikes the phosphorous content is high and leached dikes show a loss of this element so the igneous rocks appear to be the original source of it. No definite phosphorous minerals have been found, but the association of calcium and phosphorous in some of the deposits suggests the presence of apatite.

The average analysis of ore from the Mesabi district for three years shows a decrease from 60.70 per cent to 58.83 per cent in iron and a corresponding increase in phosphorous.

In the description of the Marquette district, peridotite as well as syenite is considered of Laurentian age and this fact is of interest since we have become so accustomed to thinking of this series as acid in composition. Regarding the placing of slates under the Ely Greenstone, as is done on p. 119, the question might be raised, whether it would not be better to reserve the term greenstone for lithological characters and apply it only to chemically and mineralogically altered, basic, igneous rocks.

The Keweenawan series is regarded as largely terrestrial in origin and a number of excellent reasons are given for drawing this conclusion. A few of these are: the thickness of the sediments and the frequent repetition of conglomerate beds; the feldspathic, poorly assorted and almost completely oxidized character of the sediments; the frequent occurrence of ripple-marks and mud-cracks, and the fact that the matrix of the basal conglomerate on the north shore is frequently limestone in such a condition as to suggest subaerial deposition similar to that occurring in the Bighorn Mountains at the present day.

The origin of the Keweenawan igneous rocks is assigned to fissure eruptions in the vicinity of the Lake Superior basin caused by orogenic movements and the down-warping of the basin apparently began in the Middle Keweenawan epoch. The source of the sediments is found chiefly in the underlying igneous rocks and the maximum thickness of the series is regarded as not more than half of that which was assigned to these rocks by some earlier writers. The discrepancy is due to the consideration that they were deposited on an inclined surface.

In the classification of the Keweenawan igneous rocks, p. 396, by A. N. Winchell, the term plagioclasite is used as a synonym for anorthosite. While this term is not so euphonious as anorthosite and might include rocks of greater range in chemical composition than that usually designated by this term it has simplicity and the advantage of corresponding in use to the terms amphibolite, pyroxenite, and leucitite.

The Lake Superior sandstone is for various reasons assigned to the Cambrian.

Beginning with chap. xvii the iron ores are discussed in great detail. The deposits are divided, chiefly on a genetic basis, into the pre-Cambrian sedimentary types, the source of nearly all the ore; titaniferous magnetites constituting magmatic segregations in gabbros; magnetic ores representing pegmatite intrusions in basic rocks; residual bog ores of Paleozoic age; and hematites from the Clinton series. The average iron content of all the original phases of the pre-Cambrian iron-bearing formations, not including the slates, is 24.8 per cent and the average for the ferruginous schists and jaspers is 26.33 per cent. If the average be taken for the formations including the ores the content of iron is 38 per cent showing the influence of concentration.

About $21,600,000 has been spent in diamond drilling in the region at an average cost of about $3. per foot. The average cost of mining underground is probably about $1. per ton, and the cost of transporting ore to the furnaces (in 1907) about $2.14 per ton. The stripping operations in the Mesabi district annually exceed in extent those on the Panama Canal.

The estimated reserves of pre-Cambrian ores is placed at 1,905,000,000 long tons.

The genesis of the sedimentary iron formations is the topic of greatest interest in this monograph and it is interesting to see the change of view by the senior author. He has to a large degree forsaken his earlier views which held that the iron deposits were principally the products of rock weathering for those which consider these deposits as coming chiefly either directly or indirectly from igneous rocks without the action of ordinary weathering agencies. The fact that anyone so familiar with these deposits as President Van Hise should adopt the new theory is a strong point in its favor. The hypothesis now accepted by the authors for the origin of the deposits is, briefly, that they are principally chemical sediments, that the original minerals were largely iron carbonate and silicate with some ferric oxides. The greater portion of the ore owes its present condition to secondary enrichment under special

topographical and structural conditions although a smaller portion may have been laid down originally with practically the present content of iron. The materials forming the schist, iron carbonate, and silicate are supposed to have been derived principally from basic igneous rocks either as magmatic solutions poured into the sea or from solutions of iron salts in sea water formed by the action of hot igneous rocks coming in contact with the salt water. Some of the iron was derived from these basic rocks by weathering and transported to delta deposits while other portions were deposited in bogs and lagoons through the action of plant life as bog ore is deposited at the present time. This bog and lagoon origin is assigned to the lenses of carbonate in carbonaceous slates and shales which appear to be delta deposits but the conclusions of Weidman that the Baraboo and much of the Lake Superior deposits are of this origin are not accepted. A pegmatitic origin is suggested for a portion of the iron and silica and some good evidence is presented from the Vermilion district in support of this view. A great deal of evidence is also presented to show that the ellipsoidal character of the greenstones is due to extrusion under water but on account of conflicting evidence, which has been impartially presented, it is felt that the case has not been made definite. It is argued further from the results of a large amount of data collected that ordinary weathering conditions could not produce such great deposits of chemical sediments without more clastic materials because there is not sufficient iron in the surface rocks nor adequate agencies to transport the iron to the site of deposition. These arguments are supported by a set of laboratory experiments which show that the very conditions postulated for the field can be produced in the chemical laboratory.

In these experiments it was shown that if hot Keewatin basalt be sprayed with salt water, a water-glass glaze is formed and if this water-glass be neutralized by hydrochloric acid, silicic acid and sodium chloride are produced. If the solution then be boiled it becomes alkaline. Thus is demonstrated a source for the alkaline silicates and when ferrous chloride and sodium silicate react, iron silicate (greenalite) and sodium chloride are formed. If iron silicate be attacked by carbon dioxide there is produced iron carbonate and silica. Further, if silicic acid be boiled with iron carbonate, greenalite is formed. These and many other experiments demonstrate the possible source of the material for the building up of the greenalite, siderite, and cherty deposits. Of particular interest is the statement that the precipitates of these substances show a distinct tendency toward banding.

The theory of origin as outlined in this work is the most complete exposition of the subject yet presented and it would be unreasonable to doubt, in the presence of the facts presented, the probability of the origin of a great deal of iron by its direct extraction from the igneous rocks in the manner above stated. The description of the possible origin of the banding in the jaspers is without doubt the best solution of the problem yet offered, as this feature of the deposits has always been a very difficult one to explain by any other theory. However, while it is not the purpose of this review to offer a better theory for the origin of these deposits, it might be remarked that while the authors have been fair and impartial in the presentation of this theory, which is largely new but still embodying some of the principles of one of H. N. Winchell's earlier hypotheses, there are a number of arguments which will not be accepted by those who hold that the weathering of rocks is the most important feature in the development of these deposits. It may be felt that sufficient importance has not been attached to the influence of physiographic conditions during the weathering processes, because bog deposits are developed under special topographic conditions, and the fact that so little iron was deposited in the Lower Huronian might be explained by the fact that during the early part of the epoch the relief was great and coarse clastic sediment was being deposited rapidly at the expense of the finer chemical sediments. Could not the fact that the percentage of iron in the iron formation is so large, compared with the amount of the clastics, be explained by selective transportation by which the chemical sediments were carried to lower ground and the clastics left to a greater degree on the higher levels? In the folding which followed the lower would be folded down and preserved in the synclines. Nor is the possible source of iron in the Huronian by the destruction of Keewatin iron deposits given sufficient prominence, as the amount of these rocks destroyed must have been very great. While there is comparatively little clastic sediment in the Keewatin of the Vermilion range there is much feldspathic, poorly assorted material in many other areas of iron-formation, which the authors regard as Keewatin, and which are in all other respects very similar to the Vermilion area. As to the question why there is not much iron in the great sedimentary series of the Paleozoic, which have been produced under normal weathering conditions, it may be replied that there are large deposits, without associated igneous rocks, in the Clinton series and Pennsylvanian system, both of which followed a period of extensive deposition of clastics, which represented probably subaerial conditions

and the destruction of great quantities of pre-Cambrian rocks. Although these deposits do not compare with those of the Huronian and Keewatin in extent, there never has been a period in the earth's history when such areas of fresh igneous rock in such a condition for rapid disintegration were exposed to weathering processes, nor have there been more favorable physiographic conditions for deposition than in Keewatin time. Regarding the relation of the iron-formation to different types of sediments it may be shown that the normal relation of bog deposits to clastic sediments today is that here they lie on sand and there on clay.

The origin of the copper ores of the Keweenawan is assigned chiefly to solutions of magmatic waters and to a lesser extent to the leaching of the igneous and sedimentary rocks by thermal waters. While this view is not entirely new it is much better established here than ever before by the application to the problem of rock alteration, the knowledge now possessed of the difference between the results of alteration by thermal solutions and by ordinary weathering processes. The presence of considerable chlorine in the deep-mine waters and the general scarcity of sulphides suggest that the chloride of copper was the principal compound in which the copper was originally transported. The copper was then brought to the metallic condition through the influence of ferrous compounds. The decreasing copper content of the deposits with depth is assigned to the nature of original deposition and not to secondary enrichment, as very little of the native copper is dissolved and transported.

The silver deposits on the north shore of Lake Superior are also regarded as having their origin in the Keweenawan, basic, intrusive rocks, and it is shown that chlorine is present to a marked extent in the deep-mine waters. From observations of certain similarities in geological characters it is therefore concluded that the Keweenawan copper, the Silver Islet silver, the Bruce Mines copper, the Sudbury nickel, and the Cobalt silver deposits are portions of a great metallographic province.

In a brief account of the Paleozoic rocks on p. 615, the term Proterozoic is introduced and made to include the Archean as well as the four members of the Algonkian group. This is not the sense in which the term has been used by other geologists and we surely have enough geological terms with two or more meanings. The author's use is a pointed illustration of the unsatisfactory usage which led to the adoption of the term Proterozoic, that is the illogical practice of including under a term of inferior rank the four great systems, Keweenawan, Upper Huronian (Animikie), Middle Huronian, and Lower Huronian,

as well as the unknown deposits represented by the great unconformities that lie between these. The use of Proterozoic for these four systems as a group implies that taken together they are regarded as similar in importance to the Paleozoic, Mesozoic, and Cenozoic groups. To include the still greater Archean series, with its unknown extension downward, under the term Proterozoic is to introduce a usage more unfortunate than that which preceded the adoption of the term Proterozoic. The authors of this monograph have always stood for a sharp line of demarkation between the Archean and other rocks of the pre-Cambrian. It would have been easy to have said Proterozoic and Archean and thus to have given to the group included under the name Algonkian the dignity to which it is thought to be entitled by those who use the term Proterozoic for it.

In the account of the great unconformity between the Upper Huronian and underlying rocks, given on p. 619, those who have held that the term Animikie should be applied to this as a distinct system, separated from the Huronian, will find much to justify their views.

In conclusion I would state that this monograph, aside from a few points mentioned, is logically arranged and very clearly written and, considering the number, variety, and excellence of the illustrations and having regard for the amount of detailed work, the results of which are here given, it must be considered as one of the finest publications of the Geological Survey.

E. S. MOORE

"Versuche über Umkristallisation von Gesteinen im festen Zustande." VON F. LEEWINSON LESSING. *Centralblatt für Min., etc.*, No. 19, (October 1, 1911), pp. 607–14. Figs 7.

The experiments were planned to test the validity of the assumption that certain schists and contact metamorphic rocks have developed through the recrystallization of solid phases of previously existing rocks. A hand specimen of dunite and another of pyroxenite were subjected to a temperature of from 1,200 to 1,300° for nine months without showing signs of melting. The observed changes were textural, mineralogical, and chemical. The pyroxenite became a porous, coarse-grained aggregate of yellow, monoclinic pyroxenes spotted with ferric oxide grains. The olivine of the original rock had completely disappeared. The dunite was changed from an aggregate of angular and rounded colorless olivine grains interspersed with bunches of serpentine to a rock in which no serpentine was visible, but in its place were groupings of colorless

grains of an undetermined mineral, probably orthorhombic pyroxene. The olivine had become closely compacted and the grains jagged in outline, with numerous inclusions of dark grains, probably iron oxide. Analyses of the fresh and altered rock showed that the recrystallization involved oxidation and dehydration.

E. STEIDTMANN

Geology of the Thousand Islands Region. By H. P. CUSHING, H. L. FAIRCHILD, R. RUEDEMANN, and C. H. SMYTH, JR. New York State Museum Bulletin 145. Albany, 1910. Pp. 194; Figs. 14; Pls. 63; Maps 5.

The Thousand Islands region embraces the Alexandria Bay, Cape Vincent, Clayton, Grindstone, and Theresa quadrangles of northern New York. It is a district of pre-Cambrian, Cambrian, and Lower Silurian rocks and Pleistocene deposits, which are described and faunas and structures of which are discussed.

From facts gathered outside of this district the formerly called "passage beds" lying between the Potsdam and the overlying Beekmantown have been separated into two formations, the Theresa of the Upper Cambrian and the Tribes Hill of Beekmantown age. Although the unconformity that causes the separation has not as yet been detected in this region, the paleontological evidence indicates that the separation should be made. Of special interest is the new Pamelia formation, here first differentiated, which represents an arm of the Upper Stones River sea when that sea had encroached farthest to the northeast. No deposits of the Stones River sea have previously been known to occur in New York. The Pamelia basin was entirely separated from that of the Chazy, but is considered to be contemporaneous with the interval between the Middle and Upper Chazy. The term "Black River" as applied to Lower Silurian formations, has been redefined to include, besides the "Seven foot tier" of Hall, now renamed the Watertown limestone, the Lowville formation of which the upper part (the "cherty beds") is called the Leray limestone member.

The Pleistocene deposits consist of three kinds; those formed by glaciers, those formed in the glacial Lake Iroquois, and the deposits in Gilbert Gulf, an arm of the Atlantic after Lake Iroquois had been drained to sea-level.

The pre-glacial course of Black River has a new interpretation which states it to have been the headwaters of the St. Lawrence drainage instead of the Ontario valley.

The petrography of the pre-Cambrian rocks is discussed, and numerous analyses of granites, syenites, gneisses, and amphibolites are given.

A. E. F.

An Excursion to the Yosemite (California), or Studies in the Formation of Alpine Cirques, "Steps," and Valley "Treads." By E. C. ANDREWS. Jour. and Proc. of the Royal Society of N. S. Wales, XLIV, 262–315; Figs. 17.

Considerable space is given to *The Psychological Factor in the History of the Glacial Controversy* in which is emphasized the necessity of interpreting glacial features by the ice floods that formed them, and not by the present dwarfed representatives of those floods. The dynamics of ice stream erosion is discussed with special emphasis on the effects of ice falls and their recession forming "steps" and "treads," and on the formation of cirques and *roches moutonnées*.

Previous to glacial times, the Merced and Tenaya rivers had a fairly even descent through the Yosemite region, with a notable constriction in the valley between El Capitan and the Cathedral rocks. Later, with the ice moving through this constriction, the velocity at this point was increased, and, likewise, the erosive power, which developed a "step" with "basined tread." The "step" and "tread," once formed, were rapidly enlarged by recession through the processes of sapping and quarrying, and in their recession left hanging valleys, now marked by water falls.

A. E. F.

Department of Terrestrial Magnetism of the Carnegie Institution of Washington, Annual Report of the Director. By L. A. BAUER. Year Book No. 9, pp. 195–204; Pl. 1.

In a general summary is given the work done with the "Carnegie" in correcting magnetic charts, and an outline of her present circumnavigation cruise. The field work in the various countries, the ocean work of the "Carnegie," the office work, and the shopwork accomplished during the year are stated briefly. The map (Pl. 5) accompanying the report shows the status of the magnetic work accomplished both on land and sea up to October 31, 1910, and the uncompleted portion of the present cruise of the "Carnegie."

A. E. F.